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(12) United States Patent
Gan

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(54) APPARATUS, SYSTEM, AND METHOD OF FREQUENCY GENERATION USING AN ATOMIC RESONATOR

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(73) Assignee: DIMENSION 4 LTD., Atlit (IL)

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(21) Appl. No.: 14/760,147

(22) PCT Filed: Jan. 9, 2014

(86) PCT No.: PCT/IB2014/058146

§ 371 (c)(1),
(2) Date: Jul. 9, 2015

(87) PCT Pub. No.: WO2014/108845

PCT Pub. Date: Jul. 17, 2014

(65) Prior Publication Data

US 2015/0358026 A1 Dec. 10, 2015

Related U.S. Application Data

(63) Continuation-in-part of application No. 14/056,095, filed on Oct. 17, 2013, now Pat. No. 9,201,403, which is a continuation of application No. 13/597,369, filed on Aug. 29, 2012, now Pat. No. 8,587,382, which is a

(Continued)

(51) Int. Cl.
G04F 5/14 (2006.01)
H03B 17/00 (2006.01)

(Continued)

(52) U.S. Cl.
CPC *G04F 5/14* (2013.01); *G04F 5/145* (2013.01); *H03B 17/00* (2013.01); *H03L 7/08* (2013.01); *H03L 7/26* (2013.01)

(58) Field of Classification Search
CPC G04F 5/14; G04F 5/145; H01S 1/02; H03B 17/00; H03L 7/26
USPC 331/3, 94.1
See application file for complete search history.

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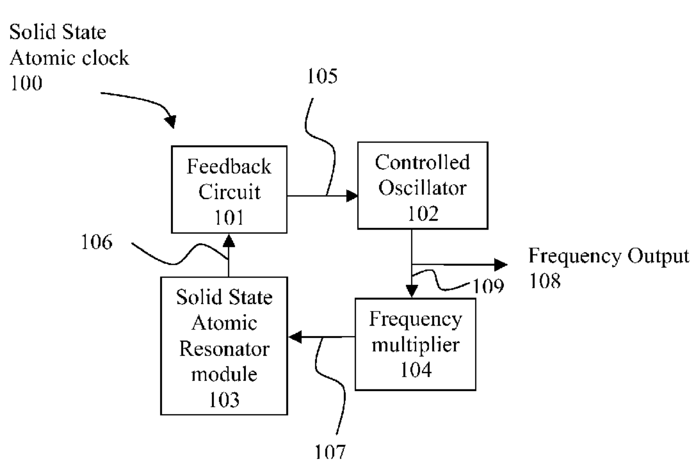
(74) *Attorney, Agent, or Firm* — Shichrur & Co.

(57) ABSTRACT

Some demonstrative embodiments include devices, systems and/or methods of generating a frequency reference using a solid-state atomic resonator formed by a solid-state material including an optical cavity having color centers. A device may include a solid-state atomic clock to generate a clock frequency signal, the solid-state atomic clock including a solid state atomic resonator formed by a solid-state material including an optical cavity having color centers, which are capable of exhibiting hyperfine transition, wherein the solid-state atomic clock may generate the clock frequency signal based on a hyperfine resonance frequency of the color centers. The device may also include a compensator to compensate for a change in one or more attributes of the solid state atomic resonator, which are to affect the hyperfine resonance frequency of the color centers.

20 Claims, 19 Drawing Sheets



Related U.S. Application Data

continuation of application No. 12/866,264, filed as application No. PCT/IL2009/000131 on Feb. 5, 2009, now Pat. No. 8,299,858.

(60) Provisional application No. 61/750,889, filed on Jan. 10, 2013, provisional application No. 61/026,744, filed on Feb. 7, 2008.

(51) **Int. Cl.**

H03L 7/26	(2006.01)
H03L 7/08	(2006.01)

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2001/0045898	A1	11/2001	Pelekis
2005/0088248	A1	4/2005	White
2007/0247241	A1	10/2007	Braun et al.
2014/0104008	A1	4/2014	Gan

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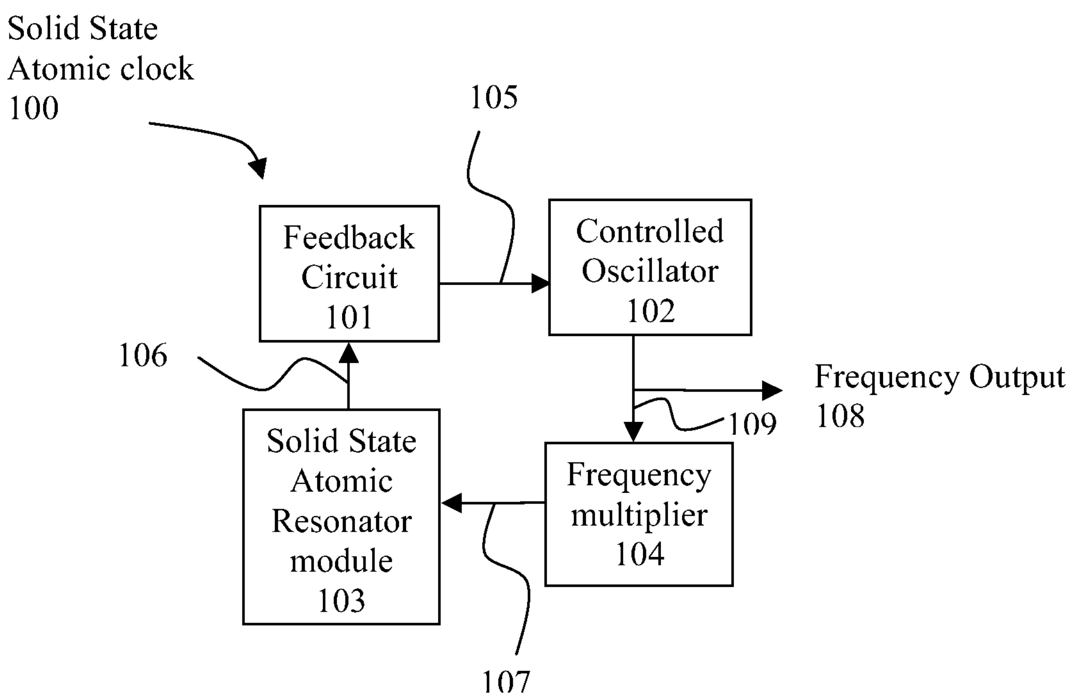

Solid State
Atomic clock
100
105
Feedback
Circuit
101
Controlled
Oscillator
102
106
Frequency Output
108
109
Solid State
Atomic
Resonator
module
103
Frequency
multiplier
104
107

FIG. 1

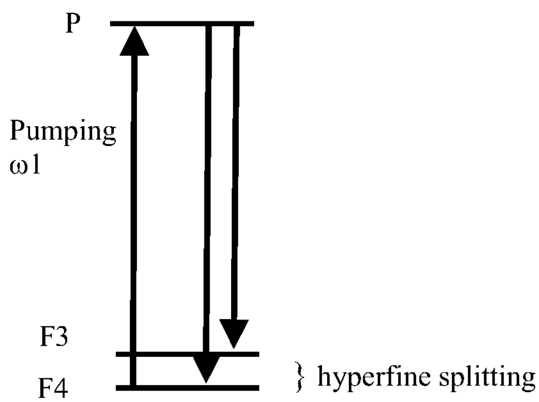


FIG. 2a Prior Art

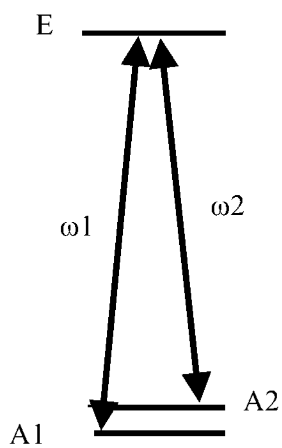


FIG. 2b Prior Art

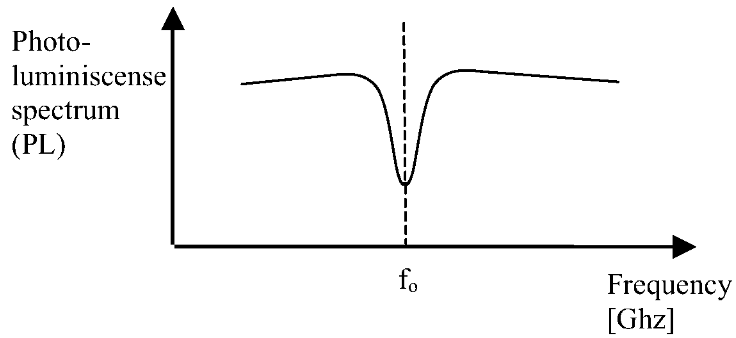


FIG. 3a

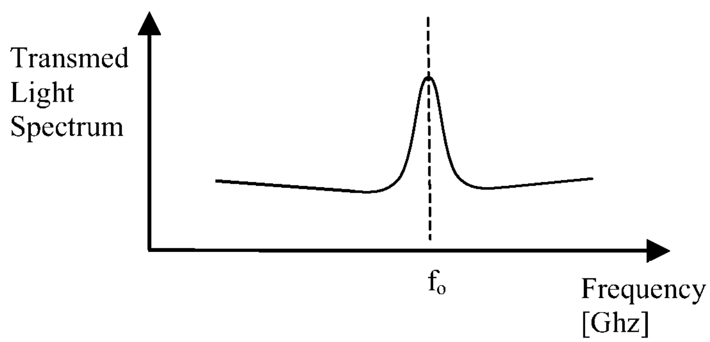


FIG. 3b

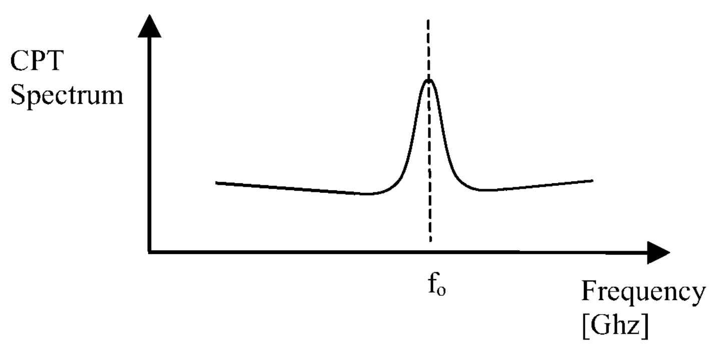


FIG. 3c

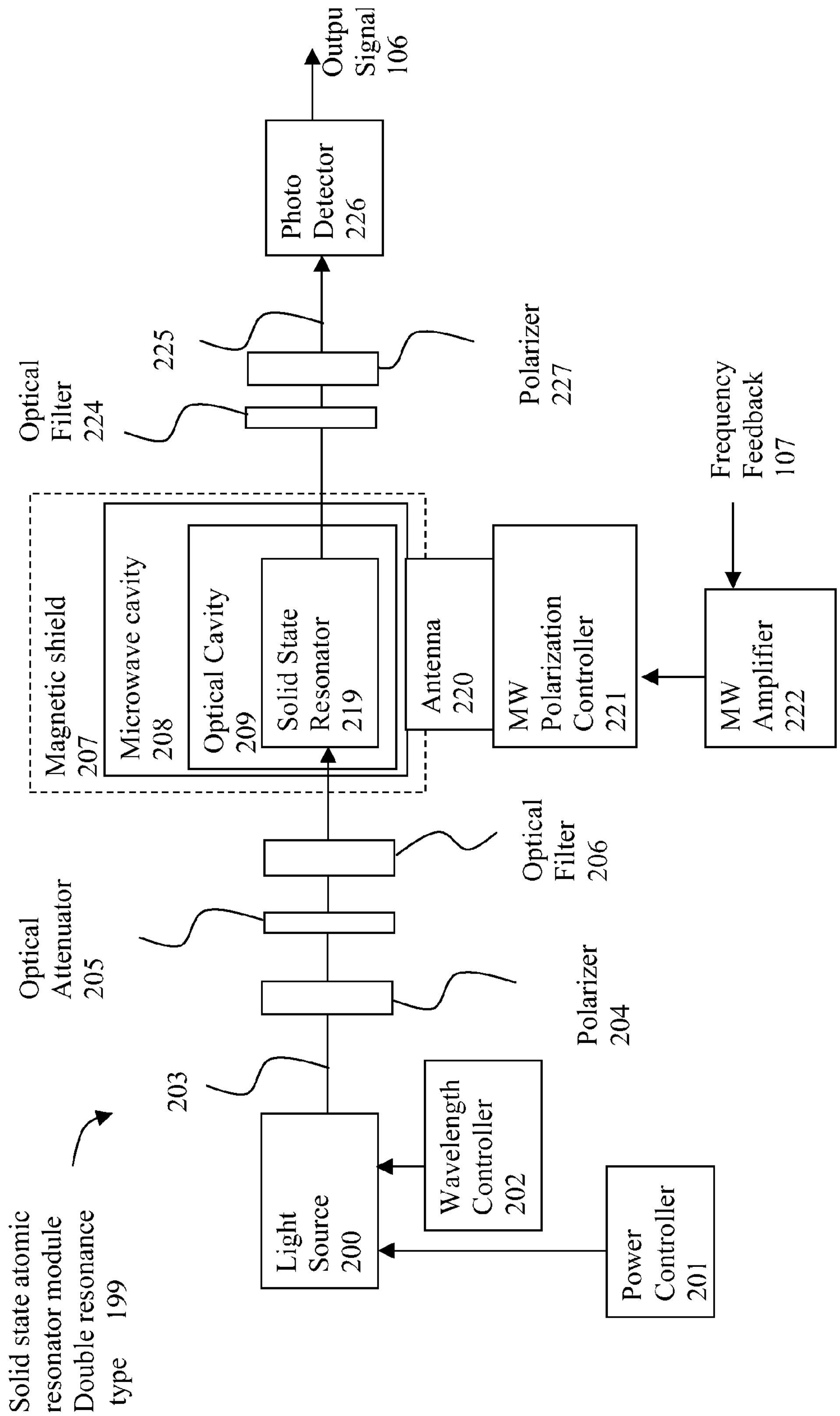

Solid state atomic resonator module Double resonance type 199
Light Source 200
Power Controller 201
Wavelength Controller 202
203
Polarizer 204
Optical Attenuator 205
Optical Filter 206
Magnetic shield 207
Microwave cavity 208
Optical Cavity 209
Solid State Resonator 219
Antenna 220
MW Polarization Controller 221
MW Amplifier 222
Frequency Feedback 107
Optical Filter 224
225
Polarizer 227
Photo Detector 226
Outpu Signal 106

FIG. 4

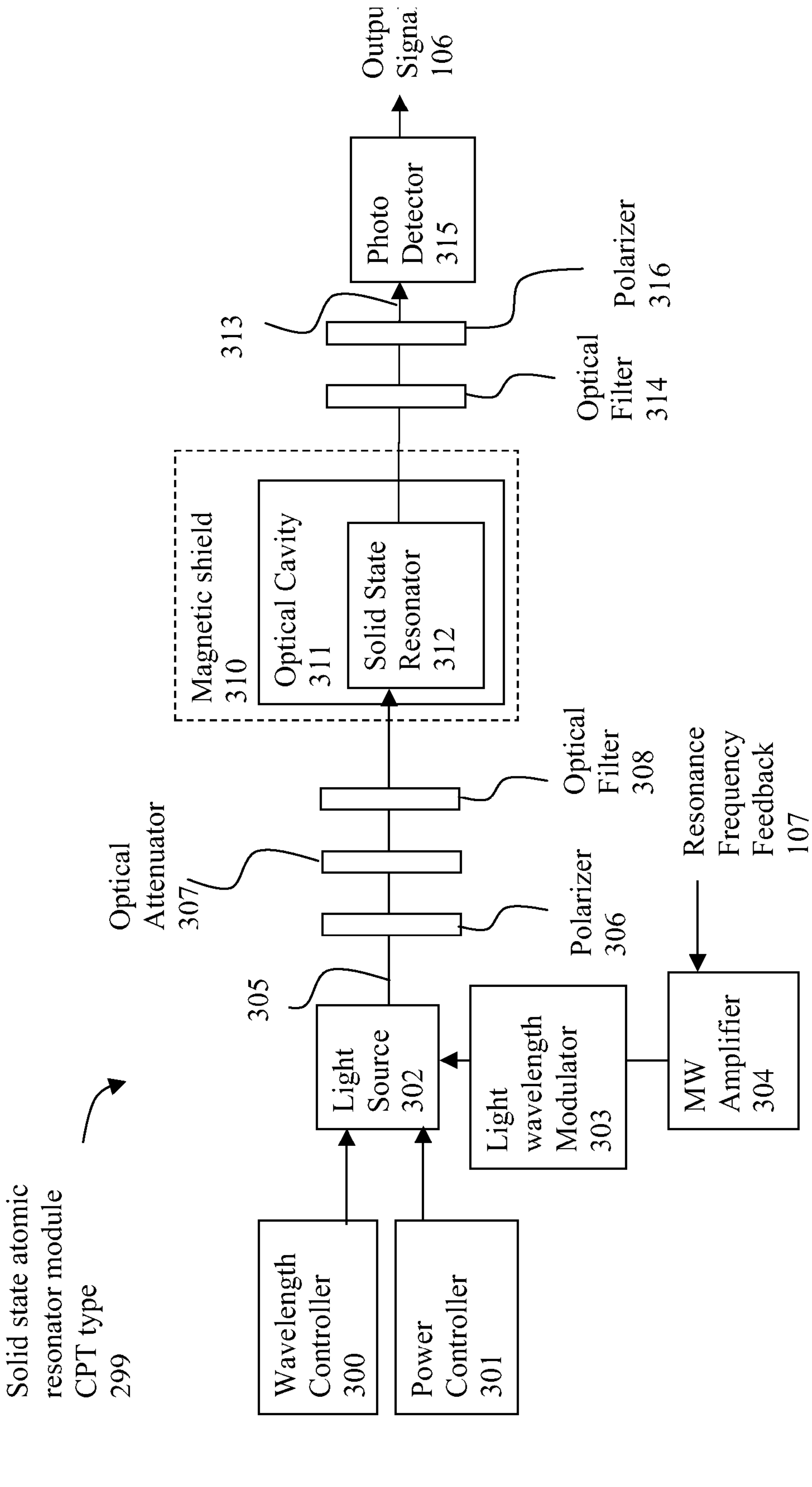

Solid state atomic resonator module CPT type 299
Wavelength Controller 300
Power Controller 301
Light Source 302
Light wavelength Modulator 303
MW Amplifier 304
305
Polarizer 306
Optical Attenuator 307
Optical Filter 308
Resonance Frequency Feedback 107
Magnetic shield 310
Optical Cavity 311
Solid State Resonator 312
Optical Filter 314
313
Polarizer 316
Photo Detector 315
Outpu
Signa
106

FIG. 5

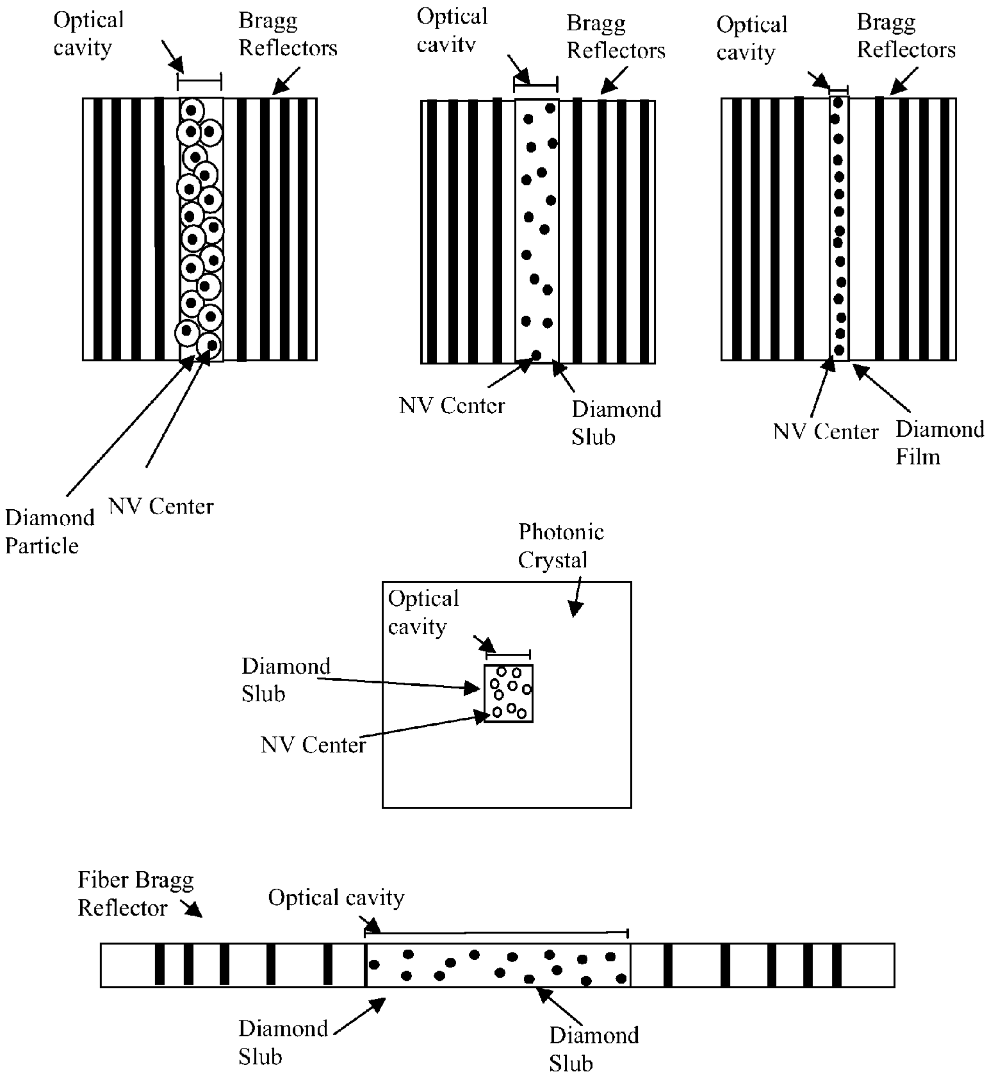

Optical
cavity
Bragg
Reflectors
Diamond
Particle
NV Center
Optical
cavitv
Bragg
Reflectors
NV Center
Diamond
Slub
Optical
cavity
Bragg
Reflectors
NV Center
Diamond
Film
Photonic
Crystal
Optical
cavity
Diamond
Slub
NV Center
Fiber Bragg
Reflector
Optical cavity
Diamond
Slub
Diamond
Slub

FIG. 6

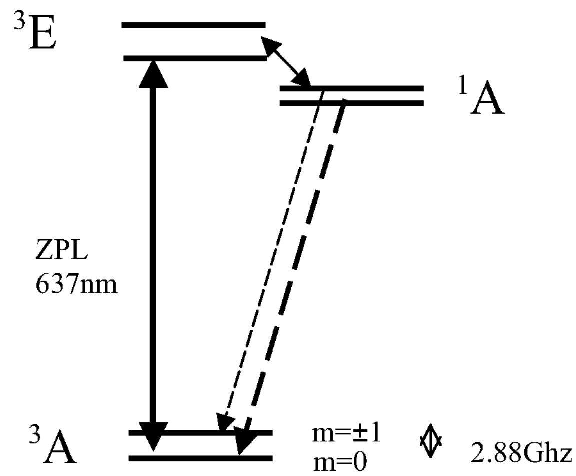


FIG. 7a

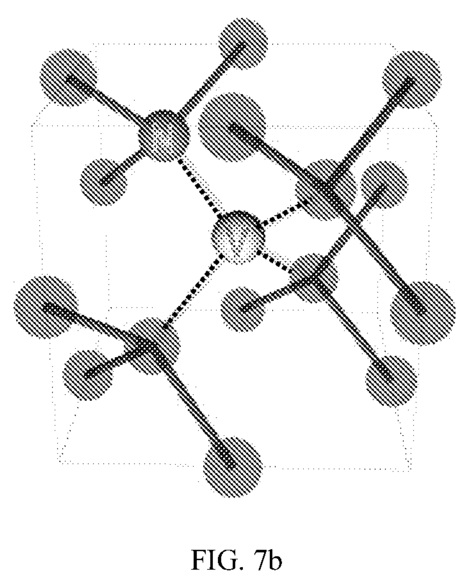


FIG. 7b

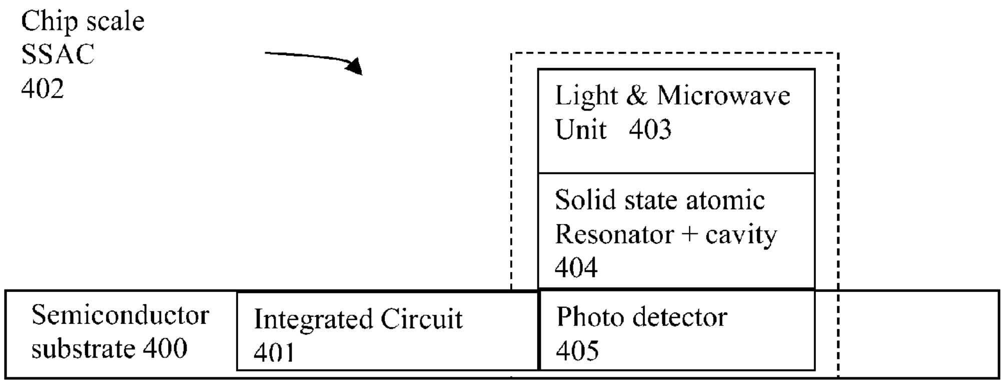


FIG. 8a

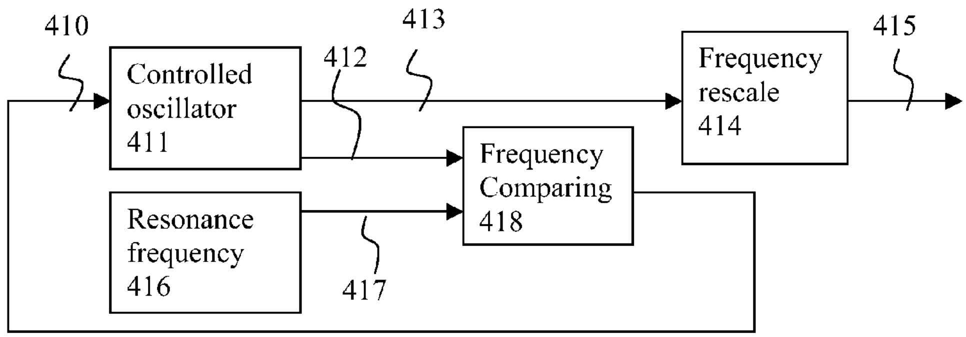


FIG. 8b

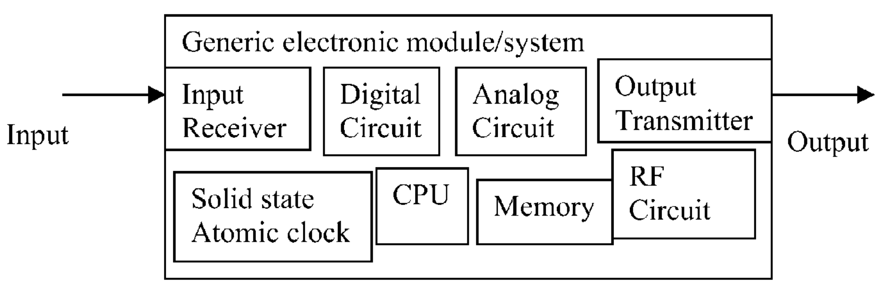


FIG. 8c

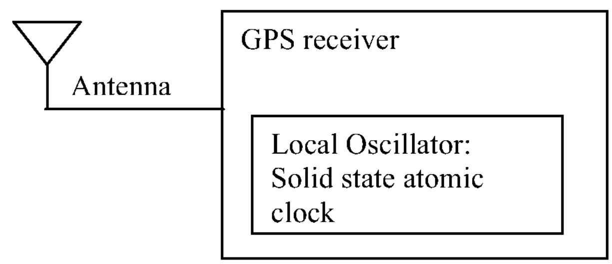


FIG. 9a

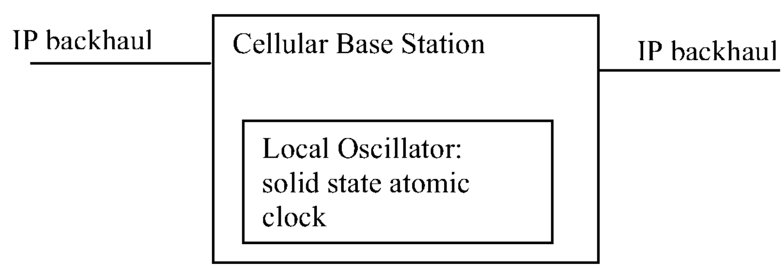


FIG. 9b

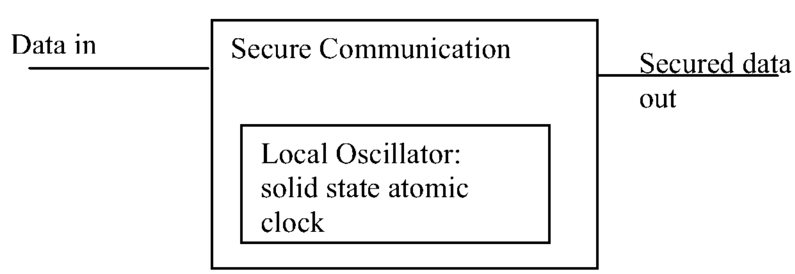


FIG. 9c

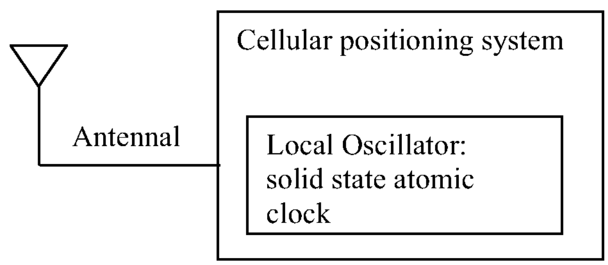
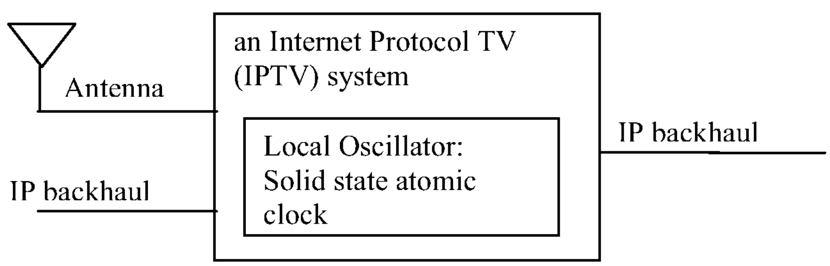


FIG. 10a



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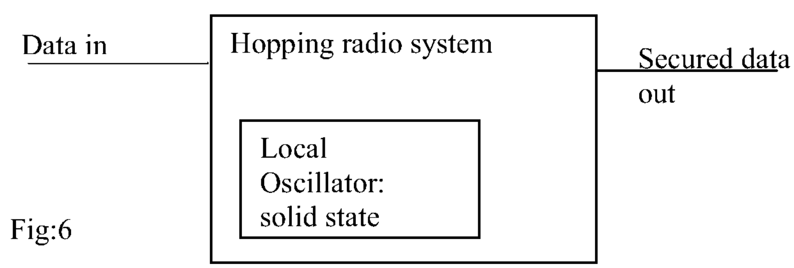

FIG. 10c

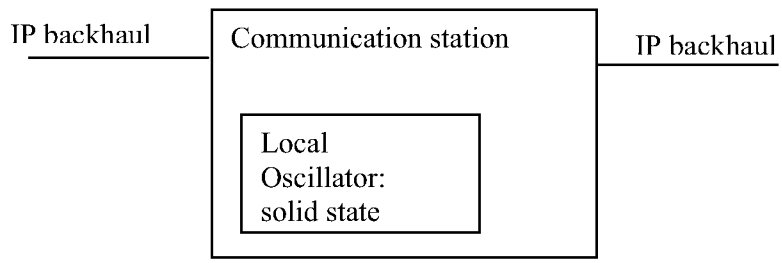

FIG. 11a

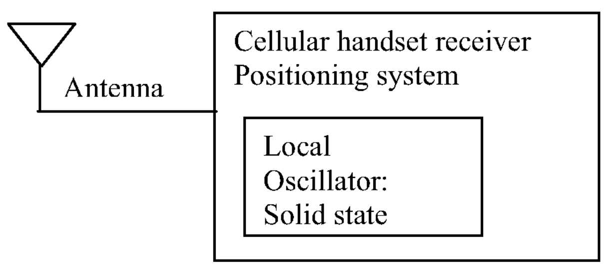

FIG. 11b

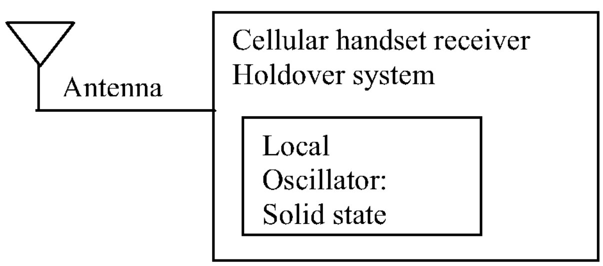

FIG. 11c

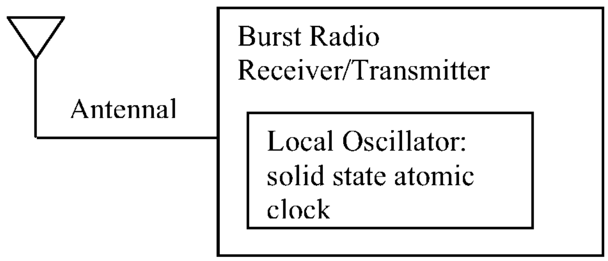

FIG. 12a

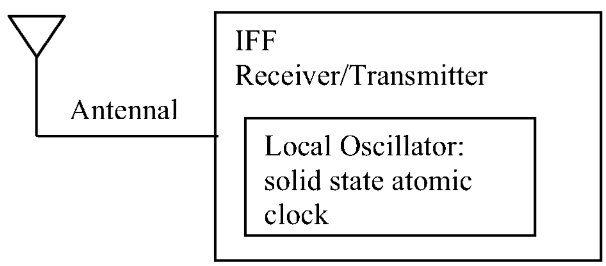

FIG. 12b

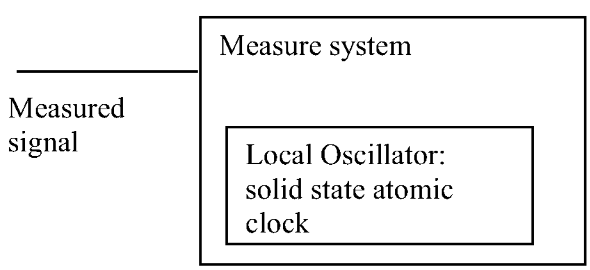

FIG. 12c

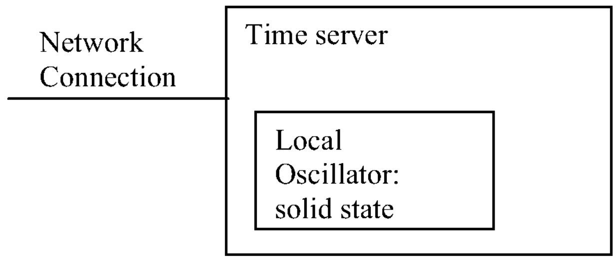

FIG. 13a

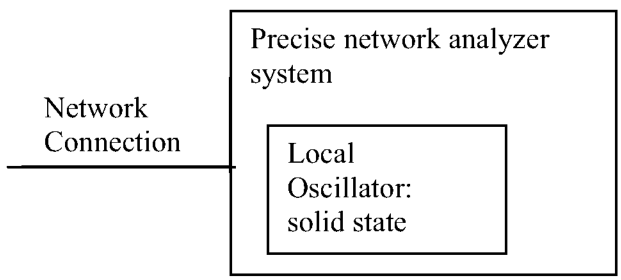

FIG. 13b

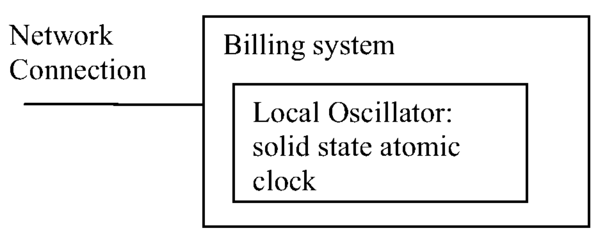

FIG. 13c

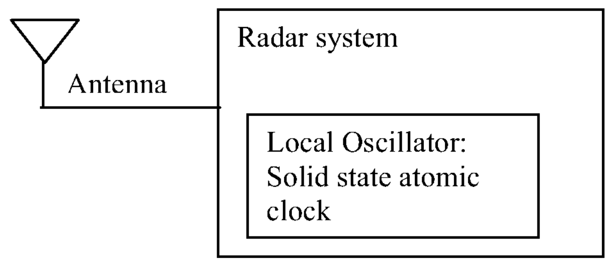

FIG. 14a

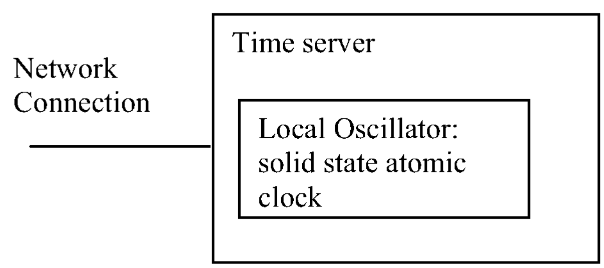

FIG. 14b

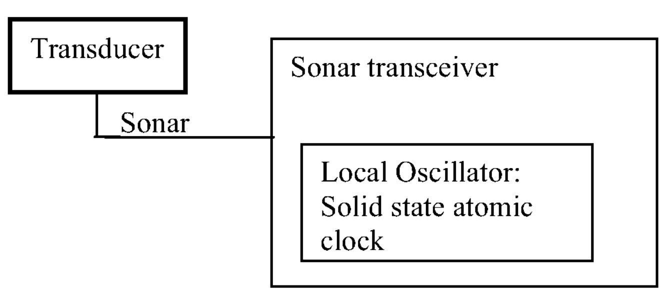

FIG. 14c

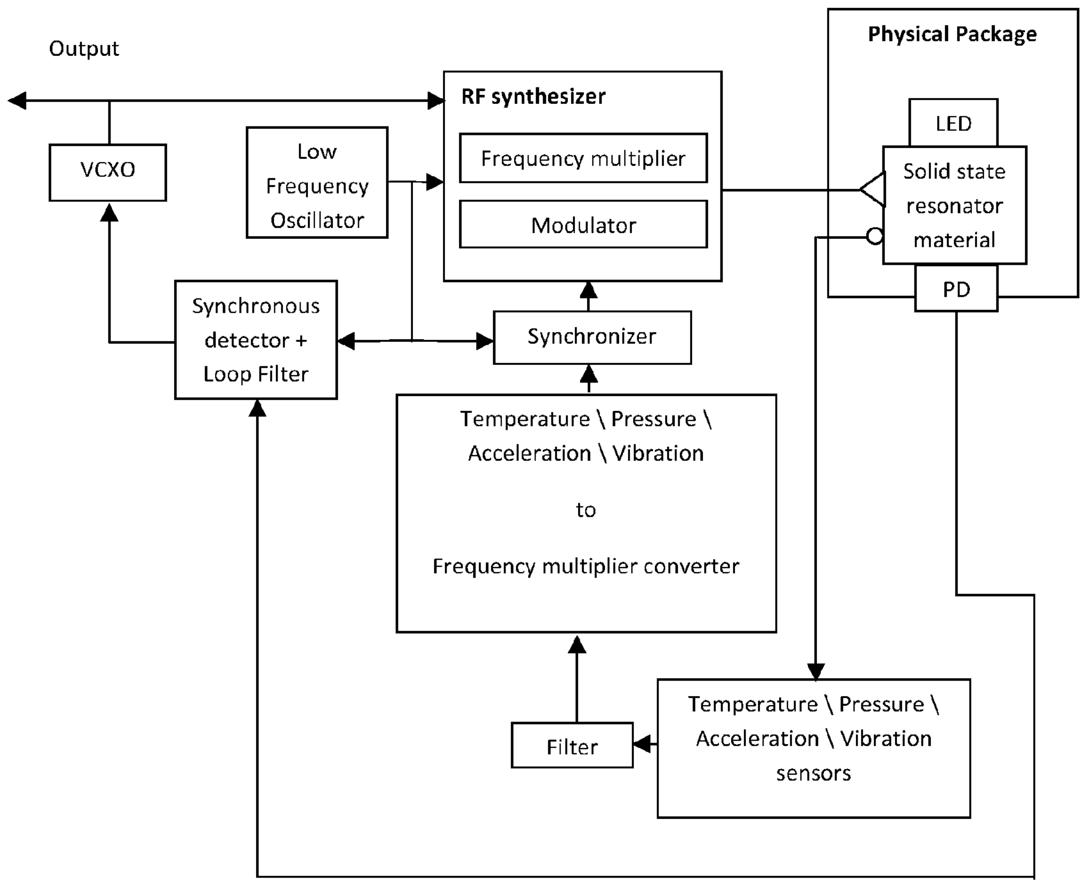
Output
VCXO
Low Frequency Oscillator
RF synthesizer
Frequency multiplier
Modulator
Physical Package
LED
Solid state resonator material
PD
Synchronous detector + Loop Filter
Synchronizer
Temperature \ Pressure \ Acceleration \ Vibration
to
Frequency multiplier converter
Filter
Temperature \ Pressure \ Acceleration \ Vibration sensors

FIG. 15

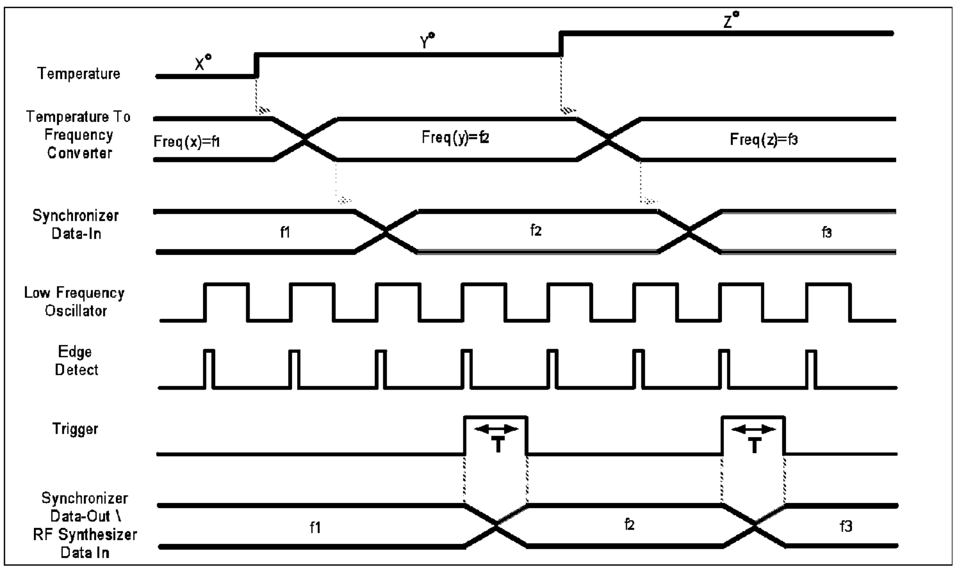
Temperature
X°
Y°
Z°
Temperature To Frequency Converter
Freq(x)=f1
Freq(y)=f2
Freq(z)=f3
Synchronizer Data-In
f1
f2
f3
Low Frequency Oscillator
Edge Detect
Trigger
T
T
Synchronizer Data-Out \ RF Synthesizer Data In
f1
f2
f3

FIG. 16

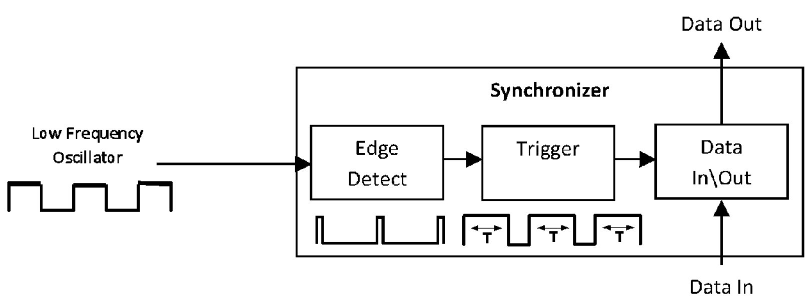
Data Out
Synchronizer
Low Frequency Oscillator
Edge Detect
Trigger
Data In\Out
T
T
T
Data In

FIG. 17

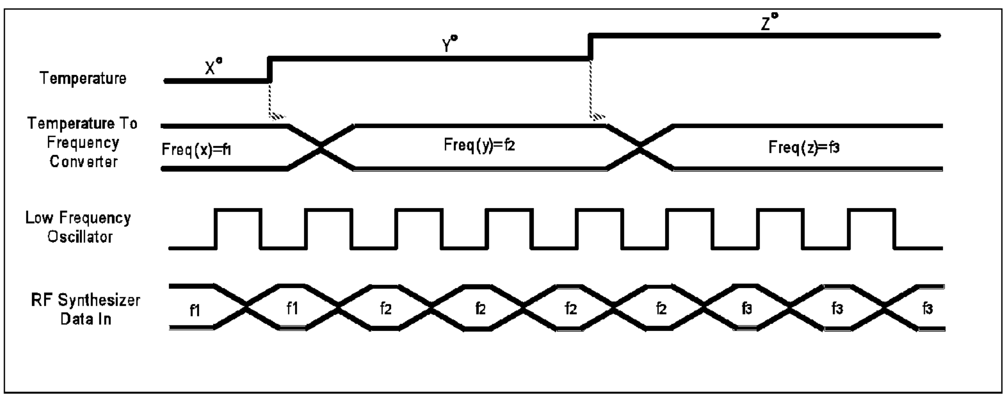
X°
Y°
Z°
Temperature
Temperature To
Frequency
Converter
Freq(x)=f1
Freq(y)=f2
Freq(z)=f3
Low Frequency
Oscillator
RF Synthesizer
Data In
f1
f1
f2
f2
f2
f2
f3
f3
f3

FIG. 18

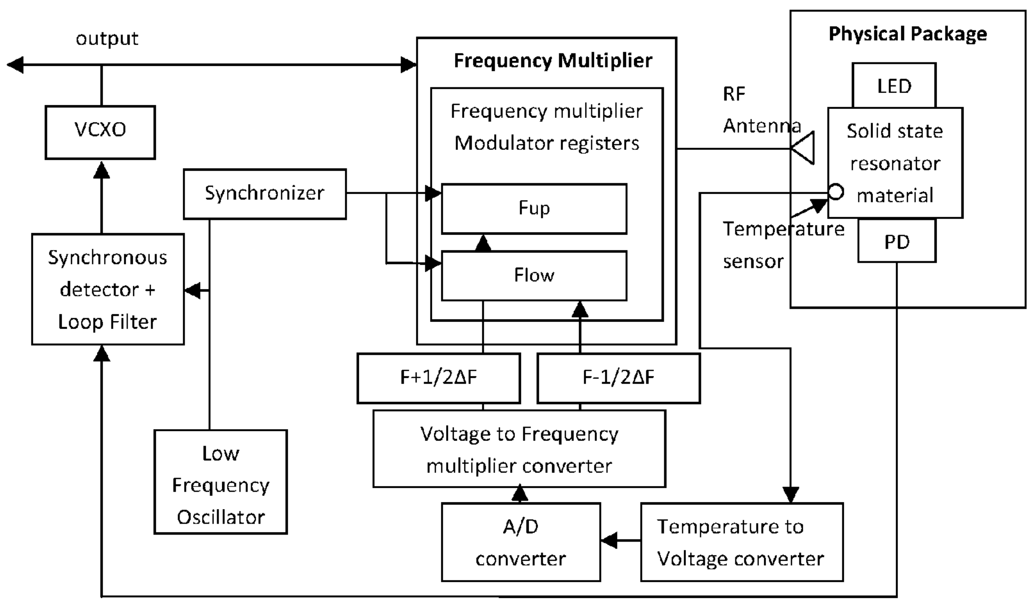
output
VCXO
Synchronizer
Synchronous detector + Loop Filter
Low Frequency Oscillator
Frequency Multiplier
Frequency multiplier Modulator registers
Fup
Flow
F+1/2ΔF
F-1/2ΔF
Voltage to Frequency multiplier converter
A/D converter
Temperature to Voltage converter
RF Antenna
Temperature sensor
Physical Package
LED
Solid state resonator material
PD

FIG. 19

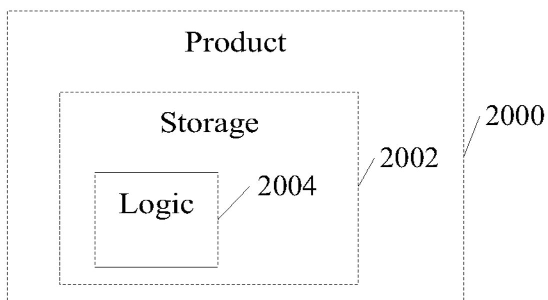

Fig. 20

APPARATUS, SYSTEM, AND METHOD OF FREQUENCY GENERATION USING AN ATOMIC RESONATOR

CROSS REFERENCE

This application claims the benefit of and priority from U.S. Provisional Patent application No. 61/750,889, filed Jan. 10, 2013, and is also a Continuation In Part (CIP) of U.S. patent application Ser. No. 14/056,095, filed on Oct. 17, 2013, which is a Continuation application of U.S. patent application Ser. No. 13/597,369, filed Aug. 29, 2012, and issued as U.S. Pat. No. 8,587,382, which is a Continuation application of U.S. patent application Ser. No. 12/866,264, filed on Aug. 5, 2010, and issued as U.S. Pat. No. 8,299,858, which is a national phase filing of PCT/IL2009/000131, filed on Feb. 5, 2009, which in turn claims the benefit of and priority from U.S. Provisional Patent application No. 61/026,744, filed Feb. 7, 2008, the entire disclosures of all of which applications are incorporated herein by reference.

FIELD

Some embodiments relate generally to the field of frequency generation, more particularly, to frequency generation using an atomic resonator.

BACKGROUND

Today, high-end frequency standard references have relatively high cost, large size, high power consumption, etc. The fast deployment of devices and/or systems such as, but not limited to, global positioning systems (GPS) and/or portable GPS systems, cellular systems and/or portable cellular phones and/or small size and low cost cellular base stations, fast telecommunications systems and other high-speed communication links, which employ very high modulation frequencies require stable, precise and accurate frequency standard reference which have small size, low cost and low power consumption.

Quartz crystals oscillators, on one hand, are the most commonly used local frequency standard, but in many cases are not sufficiently accurate, have long term frequency drift, large size and high power consumption and relatively high cost, in the case of high performance quartz crystal oscillators, these drawbacks prevent them to be suitable for the above applications.

On the other hand Rubidium (Rb) or Cesium (Cs) gas-based atomic clocks are highly accurate and they have high long-term frequency stability. However, the gas-based atomic clocks have large size, high power consumption, and high manufacturing cost.

SUMMARY

Some embodiments include, for example, devices, systems, and methods of frequency-generation using a solid-state atomic resonator.

In some demonstrative embodiments, an apparatus may include a solid-state atomic clock to generate a clock frequency signal. The solid-state atomic clock may include, for example, a solid state atomic resonator formed by a solid-state material including an optical cavity having color centers, which are capable of exhibiting hyperfine transition, wherein the solid-state atomic clock is to generate the clock frequency signal based on a hyperfine resonance frequency of the color centers; and a compensator to compensate for a change in one or more attributes of the solid state atomic resonator, which are to affect the hyperfine resonance frequency of the color centers.

In some demonstrative embodiments, the compensator may include at least one sensor to sense the one or more attributes of the solid state atomic resonator; and a frequency adjuster to cause an adjustment of the clock frequency signal based on the one or more sensed attributes of the solid state atomic resonator.

In some demonstrative embodiments, the solid-state atomic clock may include a solid-state atomic resonator module including the solid state atomic resonator. The solid-state atomic resonator module may be configured to receive an input frequency signal, which is based on the clock frequency signal, and the compensator may compensate for the change in the one or more attributes of the solid state atomic resonator by adjusting the input frequency signal to the solid-state atomic resonator module based on the one or more attributes of the solid state atomic resonator.

In some demonstrative embodiments, the solid-state atomic clock may include a solid-state atomic resonator module including the solid state atomic resonator. The solid-state atomic resonator module may be configured to receive an input frequency signal, which is based on the clock frequency signal, and the solid-state atomic resonator module may be configured to generate an error frequency signal proportional to a difference between the input frequency signal and the hyperfine resonance frequency of the color centers.

In some demonstrative embodiments, the solid-state atomic clock may include a feedback circuit configured to generate an error-correction signal based on the error frequency signal provided by the solid-state atomic resonator module; a controlled oscillator configured to generate the clock frequency signal based on the error-correction signal; and a frequency multiplier configured to generate the input frequency signal to the solid-state atomic resonator module by multiplying a frequency of the clock frequency signal.

In some demonstrative embodiments, the compensator may compensate for the change in the one or more attributes of the solid state atomic resonator by causing the frequency multiplier to adjust the input frequency signal to the solid-state atomic resonator module based on the one or more attributes of the solid state atomic resonator.

In some demonstrative embodiments, the compensator may synchronize frequencies between an adjustment of a multiplication factor of the frequency multiplier and the controlled oscillator.

In some demonstrative embodiments, the solid-state atomic resonator module may include a light source configured to generate light for illuminating the solid-state atomic resonator, and a photo detector to generate the error frequency signal based on detected photo-luminescence of the color centers.

In some demonstrative embodiments, the one or more attributes may include a temperature of the solid state atomic resonator, a pressure on the solid state atomic resonator, an acceleration of the solid state atomic resonator, and/or a vibration of the solid state atomic resonator.

BRIEF DESCRIPTION OF THE DRAWINGS

For simplicity and clarity of illustration, elements shown in the figures have not necessarily been drawn to scale. For example, the dimensions of some of the elements may be exaggerated relative to other elements for clarity of presentation. Furthermore, reference numerals may be repeated among the figures to indicate corresponding or analogous elements. The figures are listed below.

FIG. **1** schematically illustrates a solid-state atomic clock (SSAC) in accordance with some demonstrative embodiments.

FIGS. **2***a* and **2***b* are schematic energy level diagrams of hyperfine splitting, in accordance with some embodiments.

FIGS. **3***a*, **3***b* and **3***c* are schematically illustrates graphs depicting intensity versus frequency spectrum of hyperfine splitting, In accordance with some embodiments.

FIG. **4** schematically illustrates a solid-state atomic resonator module in accordance with one demonstrative embodiment.

FIG. **5** schematically illustrates a solid-state atomic resonator module in accordance with another demonstrative embodiment.

FIG. **6** schematically illustrates optical cavities embedded with NV centers in accordance with some demonstrative embodiments.

FIG. **7***a* schematically illustrates an energy diagram of an NV color center in accordance with some demonstrative embodiments.

FIG. **7***b* schematically illustrates an NV center structure in diamond in accordance with some demonstrative embodiments.

FIG. **8***a* schematically illustrates a chip including a solid-state atomic clock in accordance with some demonstrative embodiments.

FIG. **8***b* schematically illustrates a principal method of obtaining a frequency reference standard from atomic resonance in accordance with some demonstrative embodiments.

FIG. **8***c* schematically illustrates a generic electronic module and/or system utilizes a solid state atomic clock in accordance with some demonstrative embodiments.

FIG. **9***a* schematically illustrates a GPS receiver in accordance with some demonstrative embodiments.

FIG. **9***b* schematically illustrates a cellular base station in accordance with some demonstrative embodiments.

FIG. **9***c* schematically illustrates a secure communication system in accordance with some demonstrative embodiments.

FIG. **10***a* schematically illustrates a cellular positioning system in accordance with some demonstrative embodiments.

FIG. **10***b* schematically illustrates an Internet Protocol TV (IPTV) system in accordance with some demonstrative embodiments.

FIG. **10***c* schematically illustrates a hopping radio system in accordance with some demonstrative embodiments.

FIG. **11***a* schematically illustrates a communication station in accordance with some demonstrative embodiments.

FIG. **11***b* schematically illustrates cellular handset receiver with a positioning system in accordance with some demonstrative embodiments.

FIG. **11***c* schematically illustrates a cellular handset receiver with a holdover system in accordance with some demonstrative embodiments.

FIG. **12***a* schematically illustrates a burst radio communication system in accordance with some demonstrative embodiments.

FIG. **12***b* schematically illustrates an Identification Friend or Foe (IFF) module in accordance with some demonstrative embodiments.

FIG. **12***c* schematically illustrates a measuring module and/or measuring system in accordance with some demonstrative embodiments.

FIG. **13***a* schematically illustrates a time-server in accordance with some demonstrative embodiments.

FIG. **13***b* schematically illustrates a precise network analyzer system in accordance with some demonstrative embodiments.

FIG. **13***c* schematically illustrates a billing system in accordance with some demonstrative embodiments.

FIG. **14***a* schematically illustrates a radar system in accordance with some demonstrative embodiments.

FIG. **14***b* schematically illustrates a time-server in accordance with some demonstrative embodiments.

FIG. **14***c* schematically illustrates a sonar system in accordance with some demonstrative embodiments.

FIG. **15** schematically illustrates a SSAC including a temperature compensation scheme, in accordance with some demonstrative embodiments.

FIG. **16** schematically illustrates a timing sequence of a temperature update, in accordance with some demonstrative embodiments.

FIG. **17** schematically illustrates a synchronizer, in accordance with some demonstrative embodiments.

FIG. **18** schematically illustrates writing cycles of a temperature update, in accordance with some demonstrative embodiments.

FIG. **19** schematically illustrates a SSAC including another temperature compensation scheme, in accordance with some demonstrative embodiments.

FIG. **20** schematically illustrates a product of manufacture, in accordance with some demonstrative embodiments.

DETAILED DESCRIPTION

In the following detailed description, numerous specific details are set forth in order to provide a thorough understanding of some embodiments. However, it will be understood by persons of ordinary skill in the art that some embodiments may be practiced without these specific details. In other instances, well-known methods, procedures, components, units and/or circuits have not been described in detail so as not to obscure the discussion.

Unless specifically stated otherwise, as apparent from the following discussions, it is appreciated that throughout the specification discussions utilizing terms such as "processing," "computing," "calculating," "determining", or the like, refer to the action and/or processes of a computer or computing system, or similar electronic computing device, that manipulate and/or transform data represented as physical, such as electronic, quantities within the computing system's registers and/or memories into other data similarly represented as physical quantities within the computing system's memories, registers or other such information storage, transmission or display devices. In addition, the term "plurality" may be used throughout the specification to describe two or more components, devices, elements, parameters and the like.

It should be understood that some embodiments may be used in a variety of applications. Although embodiments of the invention are not limited in this respect, one or more of the methods, devices and/or systems disclosed herein may be used in many applications, e.g., civil applications, military applications or any other suitable application.

A frequency standard requires a physical frequency resonance as a frequency reference. This resonance should have long term frequency stability, low cost, small size and low power consumption. The most common resonance used in frequency are mechanical resonance of pure atomic crystals (for example quartz crystals) and/or by transitions between quantum states in atoms, ions and molecules (for example in Rb and Cs). In most of such transitions correspond to optical frequencies, which makes the transition difficult to couple to an electrical signal or in other cases the frequency difference is too low to allow a high frequency accuracy.

In general, frequency sources are divided into two categories: crystal oscillators and atomic clocks.

Crystal oscillators are based on a mechanical resonance of a quartz crystal. Such oscillators have very poor temperature stability. Crystal oscillators vary from free running oscillators with very low frequency stability and accuracy to oven temperature controlled crystal (OCXO) oscillator with rather good short-term frequency accuracy and stability (still less than that of an atomic clocks). However, even though OCXO have good short term frequency stability their long-term frequency stability is poor (over long periods of time—days, weeks or months—their frequency will drift). Moreover, they have high power consumption and/or a large size. Another drawback of the crystal oscillators is the low manufacturing yield of the resonator. Usually, the resonator is a precise cut of a quartz crystal the crystal cutting should be very accurate and along a special direction of the quartz crystal. The complexity of this process is very high and any deviation will result in an error in the resonance frequency. Therefore, the yield is low for such oscillators and as a result the manufacturing cost is high. Furthermore, crystal oscillator cannot be fully integrated on a silicon substrate and/or an electronic integrated circuits.

Gas-based atomic clocks are based on the atomic energy transition in Rb or Cs atoms in gas phase. These types of atomic clocks use atomic energy levels to generate a long-term stable and highly accurate frequency output. Typically, gas based atomic clocks use the hyperfine energy level splitting of Rb or Cs atoms in a gas state as the frequency resonance. The traditional atomic clocks are expensive, large and require high power consumption. These characteristics prevent atomic clocks from becoming a commodity. Even though small size atomic clocks can be realized, they still suffer from the drawbacks described here, this technology is immature up to date.

A gas-based atomic clock includes an atomic resonator, which includes a cell filled with a vapor of Rubidium-87 or Cesium-133 atoms. These atoms have very accurate and stable hyperfine ground state energy splitting. Therefore, an accurate and stable frequency signal may be generated by coupling an external electromagnetic field to this energy level splitting. This type of gas-based atomic clocks may have very high long-term frequency accuracy, may be very reliable, and for more than sixty years have been the most accurate commercial atomic clocks available. However, the gas-based atomic clocks suffer from the following drawbacks: high power consumption; high cost; large size; relatively high sensitivity to G-shock; long warm up time; the cell should be heated to a constant working temperature, and it is very complex to assemble and to manufacture. Furthermore, crystal oscillator cannot be fully integrated on a silicon substrate and/or electronic integrated circuits. These drawbacks prevent the gas-based atomic clocks from becoming small and to be integrated into portable and low cost applications.

Some atomic resonators utilize the double resonance technique by applying an electromagnetic optic and microwave RF fields may be implemented for the control of the hyperfine transition, e.g., as described below.

Rubidium or Cesium with hyperfine ground energy level splitting F**4** is presented in FIG. **2***a*. and FIG. **2***b*. Optical pumping, with a frequency oil corresponding to the transition from the ground energy level F**4** to the exited energy level P, may be used to excite only the electrons from the F**4** energy state in Rb/Cs atom gas to the exited state P. The exited electrons in the exited energy level P are relaxed to both the F**4** and F**3** states evenly. However, only electrons from the energy level F**4** state are excited again due to the optical pumping. Therefore, in steady state the F**3** state becomes over populated at this point the absorption of the pumping photons reach a steady state as well. Applying a microwave RF electromagnetic wave with a frequency equal to the frequency difference between the F**4** to F**3** states, may convert the F**3** electron state to the F**4** state, which provides more electrons to absorb light. Therefore, the electromagnetic wave with this particular microwave frequency results in an increase of light absorption, e.g., a dip in the absorption is presented in the absorption of the pumping light at the microwave frequency equals to the hyperfine transition. This dip in the microwave spectrum may be detected by a photodetector. A servo feedback locks the frequency of the microwave electromagnetic wave thereby to control the oscillator frequency according to the atomic transition. Usually, in this configuration the gas cell is placed in a microwave cavity and illuminated from one of the sides of the cavity.

As shown in FIG. **2***b*, in some atomic resonators a coherent population trapping (CPT) technique is used. In this cases a microwave modulated electromagnetic optic field, which has of two and/or more than two sidebands may be implemented for the control of the hyperfine transition, e.g., as described below.

As shown in FIG. **2***b*, CPT resonance may induced by two coherent optical electromagnetic fields with a frequencies ω**1** and ω**2** corresponding to the energy transition from A**1** to E and from A**2** to E in atomic system, respectively, e.g., by a light source. The frequency difference between the frequencies of the two electromagnetic fields ω**1** and ω**2** separating the two coherent optical fields is equal to the energy difference between the two low energy levels A**1** and A**2** divided by the Plank constant h. This optical field is applied to an atomic resonance. The atomic resonator which has at least one low energy state with a small energy split between the two levels and at least one high energy state that electrons can be excited to, from the two hyperfine spited low energy states A**1** and A**2**. The first frequency component ω**1** in the applied electromagnetic field excites electrons from one of the low energy states A**1** to the high energy state E while the other frequency component excites electrons from the other low energy state A**2** to the same high energy state E. Thus, the atomic resonator absorbs the energy from the two components of the applied electromagnetic field simultaneously. When the frequency difference between the two frequency components is equal to the frequency difference between the two low energy states in the atomic resonator, the atomic resonator can be in a linear superposition of the two low energy states, such that at this quantum state the atomic resonator does not interact with the applied electromagnetic field any more. This quantum state and the resulting behavior is called CPT. In this state the atomic resonator exhibits an absorption minimum, or a transmission maximum, or a minimum of luminescence see FIG. **3***a* **3***b* and/or **3***c* correspondingly. Therefore, a, for example, when the frequency difference between the two frequencies components is exactly equal to the frequency difference between two low energy states in the atomic resonator. A photo detector may be used to measure the intensity of one of the above quantities. A photo-detector measure a signal quantity which is corresponding to the error between the two frequencies ω**1** ω**2** to the frequency difference in the hyperfine energy splitting, this error signal is feedback to a servo loop, which may be used to adjust the frequency difference of the two frequency components produced by the light source, such that the error between the two frequencies ω**1** ω**2** to the frequency difference in the hyper fine energy splitting is kept to that the maximum/minimum, e.g., as shown in FIG. **3***a* **3***b* and/or **3***c*. Hence, the frequency difference of the two frequency components may be held at a precise value corresponding to the frequency difference in energy split in the low energy states of the atomic resonator. The frequency standard precision and stability may correspond to the precision and stability of the difference between the split in the energy of the low states in the atomic resonator.

In some demonstrative embodiments, a device may include a Solid State Atomic Clock (SSAC) to generate a clock frequency signal. The solid-state atomic clock may include a solid state atomic resonator formed by a solid-state material including an optical cavity having color centers, which are capable of exhibiting hyperfine transition, wherein the solid-state atomic clock generates the clock frequency signal based on a hyperfine resonance frequency of the color centers, e.g., as described in detail below.

In some demonstrative embodiments, the solid-state atomic clock includes a solid-state atomic resonator module including the solid state atomic resonator. The solid-state atomic resonator module may be configured to receive an input frequency signal, which is based on the clock frequency signal. The solid-state atomic resonator module may be configured to generate an error frequency signal proportional to a difference between the input frequency signal and the hyperfine resonance frequency of the color centers, e.g., as described in detail below.

In some demonstrative embodiments, the solid-state atomic clock may include a feedback circuit configured to generate an error-correction signal based on the error frequency signal provided by the solid-state atomic resonator module; a controlled oscillator configured to generate the clock frequency signal based on the error-correction signal; and a frequency multiplier configured to generate the input frequency signal to the solid-state atomic resonator module by multiplying a frequency of the clock frequency signal, e.g., as described below.

In some demonstrative embodiments, the solid state atomic resonator module may include a double resonance resonator, which may include a light source configured to generate light for illuminating the solid-state atomic resonator; a microwave element configured to transmit a microwave electromagnetic wave upon the solid state atomic resonator based on the input frequency signal to the solid-state atomic resonator module; and a photo detector to generate the error frequency signal based on photo-luminescence of the color centers, e.g., as described below.

In some demonstrative embodiments, the solid state atomic resonator module may include a Coherent-Population-Trapping (CPT) resonator, which may include a modulated coherent light source configured to generate light for illuminating the solid-state atomic resonator based on the input frequency signal to the solid-state atomic resonator module; and a photo detector to generate the error frequency signal based on photo-luminescence of the color centers, e.g., as described below.

In some demonstrative embodiments, the solid-state material may include diamond, and wherein the color centers may include Nitrogen-Vacancy color centers in the diamond, e.g., as described below.

In some demonstrative embodiments, the solid-state material may include at least one diamond crystal embedded by Nitrogen-Vacancy color centers, e.g., as described below.

In some demonstrative embodiments, the at least one diamond crystal may include a diamond plurality of nano-crystals, e.g., as described below.

In some demonstrative embodiments, the optical cavity may be formed by a plurality of bragg reflectors, e.g., as described below.

In some demonstrative embodiments, the optical cavities may be formed by a photonic crystal structure, e.g., as described below.

In some demonstrative embodiments, the solid-state atomic clock may be integrated on a single semiconductor substrate, e.g., as described below.

In some demonstrative embodiments, the device may include an electronic module to receive the clock frequency signal and perform an operation based on the clock frequency signal, e.g., as described below.

In some demonstrative embodiments, a method for obtaining a frequency reference may include illuminating a solid state atomic resonator formed by a solid-state material including an optical cavity having color centers, such that the color centers exhibit hyperfine transition; and generating the a clock frequency signal based on a hyperfine resonance frequency of the color centers, e.g., as described herein.

In some demonstrative embodiments, the method may include determining an error frequency based on a relationship between the clock frequency signal and the hyperfine resonance frequency of the color centers; and adjusting the clock frequency signal based on the error frequency.

In some demonstrative embodiments, the SSAC may include one or more compensation mechanisms and/or modules to compensate for a change in one or more attributes of the solid state atomic frequency resonator, which may affect the resonance frequency of the solid state material and, accordingly, may affect the accuracy and/or stability of the output frequency of the clock, e.g., as described in detail below.

Some demonstrative embodiments are described herein with respect to a SSAC including a temperature compensation mechanism to adjust the output frequency of the clock in response a change in a temperature of the solid state atomic frequency resonator. However, in other embodiments, the SSAC may include, additionally or alternatively, any other suitable mechanism to compensate for any other one or more attributes of the solid state atomic frequency resonator. For example, the SSAC may include, additionally or alternatively, an acceleration-compensation mechanism to compensate for the affect of acceleration on the resonance frequency of the solid state material; a pressure-compensation mechanism to compensate for the affect of atmospheric-pressure on the resonance frequency of the solid state material; and/or a vibration-compensation mechanism to compensate for the affect of vibration on the resonance frequency of the solid state material.

In some demonstrative embodiments, as discussed below, a solid state atomic clock may include a solid state atomic frequency resonator, a feedback loop filter, a voltage controlled oscillator and a RF frequency synthesizer. The RF frequency output may be related to the frequency of the voltage controlled oscillator by a frequency ratio. These may be connected together in a way that the frequency of the voltage controlled oscillator is locked to the frequency resonance of the solid state material, e.g., as described below. Thus, the frequency accuracy and stability of the clock output may be subject to variations due to change in the resonance frequency of the solid state material, e.g., due to acceleration, temperature, atmospheric pressure, vibration, and the like.

In some demonstrative embodiments, in the case of solid state frequency resonator based on NV color centers in diamond, the atomic resonance of 2.875 Ghz may have a temperature linear coefficient, for example, of about 75 Khz/oc. A compensation mechanism may be utilized, for example, in order to reduce, minimize and/or eliminate the temperature dependence of the output frequency due to the change in the atomic resonance. A compensation scheme may be configured, for example, to measure the diamond temperature, e.g., by an accurate temperature sensor, to calculate a frequency ratio, e.g., by a temperature to frequency ratio conversion formula, and to correct the RF frequency, e.g., according to the calculated frequency ratio.

In some demonstrative embodiments, a solid state atomic clock based on NV color centers at a constant temperature may have a frequency accuracy equal to or greater than OCXO, and it can be fabricated on a silicon chip, e.g., as described herein. This will result in low cost small size and low power consumption device.

In the solid state atomic clock based on NV centers in diamond, the resonance frequency of NV centers in diamond may change due to temperature change in the material. This may result in a change in the clock output frequency. In the case of the hyperfine energy splitting in the ground state of NV center in diamond the energy difference change as a result of the change of the diamond temperature and its surroundings. This change in the resonance frequency may result in a change of the clock frequency and/or may affect the clock accuracy. The change in the temperature and, accordingly, the corresponding correction of the frequency may occur randomly and arbitrarily. Changing the frequency at an arbitrary way, which is not synchronized to the modulation frequency, may result in an excessive noise.

Some demonstrative embodiments are described with respect to synchronizing between two elements, e.g., signals. The verb "synchronize" may relate to matching, coordinating, harmonizing, and/or synchronizing between at least one attribute of the first and second elements. The synchronizing between the first and second elements may not necessarily require matching one or more other attributes or all attributes of the first and second elements. For example, synchronizing between first and second signals may include matching between a first frequency of the first signal and a second frequency of the second signal, for example, while not necessarily synchronizing between one or more other attributes of the first and second signals, e.g., while not necessarily synchronizing between phases of the first and second signals.

In some demonstrative embodiments, the temperature of the diamond may be maintained, e.g., substantially fixed and/or constant, for example, by using a temperature controller, temperature probe and a heater. The diamond is heated to above of the ambient temperature; the temperature controller measures the temperature of the diamond and change to the diamond temperature by controlling the heating power of the heater. This method can fix the temperature of the diamond and/or stabilize the temperature of the diamond up to 0.005 deg Celsius.

In some demonstrative embodiments, the temperature of the diamond may be measured, and the resonance frequency may be adjusted, for example, by applying a magnetic field which shifts the resonance frequency by an amount equal to the frequency which was changed by the temperature in a way which will cancel the total shift by the temperature.

FIG. **15** schematically illustrates a SSAC including a temperature compensation scheme, in accordance with some demonstrative embodiments. The SSAC of FIG. **15** may be implemented as part of a device or system, e.g., a device or system as described below with reference to FIGS. **9**A-**14**C.

As shown in FIG. **15**, the atomic clock may include solid state atomic frequency resonator, a Synchronous detector and feedback loop filter, a voltage controlled oscillator and a RF frequency multiplier (synthesizer) with a frequency modulator. One or more components of the SSAC of FIG. **15** may include one or more of the components of the SSAC described herein with reference to **1**-**8**C.

In some demonstrative embodiments, the solid-state atomic clock may be configured to generate a clock frequency signal. For example, the solid state atomic resonator may be formed by a solid-state material including an optical cavity having color centers, which are capable of exhibiting hyperfine transition, and the solid-state atomic clock may be configured to generate the clock frequency signal based on a hyperfine resonance frequency of the color centers, e.g., as described in detail below.

In some demonstrative embodiments, the solid-state atomic clock may also include a compensator to compensate for a change in one or more attributes of the solid state atomic resonator, which are to affect the hyperfine resonance frequency of the color centers, e.g., as described below.

In some demonstrative embodiments, the solid-state atomic clock may include at least one sensor to sense the one or more attributes of the solid state atomic resonator; and a frequency adjuster to cause an adjustment of the clock frequency signal based on the one or more sensed attributes of the solid state atomic resonator, e.g., as described below.

In some demonstrative embodiments, the solid-state atomic clock may include a solid-state atomic resonator module (also referred to as "physical package") including the solid state atomic resonator, and the solid-state atomic resonator module may be configured to receive an input frequency signal, which is based on the clock frequency signal, e.g., as described below.

In some demonstrative embodiments, the compensator may be configured to compensate for the change in the one or more attributes of the solid state atomic resonator by adjusting the input frequency signal to the solid-state atomic resonator module based on the one or more attributes of the solid state atomic resonator.

In some demonstrative embodiments, the solid-state atomic resonator module may be configured to generate an error frequency signal proportional to a difference between the input frequency signal and the hyperfine resonance frequency of the color centers, e.g., as described below.

In some demonstrative embodiments, the solid-state atomic clock may include a feedback circuit configured to generate an error-correction signal based on the error frequency signal provided by the solid-state atomic resonator module; a controlled oscillator configured to generate the clock frequency signal based on the error-correction signal; and a frequency multiplier configured to generate the input frequency signal to the solid-state atomic resonator module by multiplying a frequency of the clock frequency signal, e.g., as described below.

In some demonstrative embodiments, the compensator may be configured to compensate for the change in the one or more attributes of the solid state atomic resonator by causing the frequency multiplier to adjust the input frequency signal to the solid-state atomic resonator module based on the one or more attributes of the solid state atomic resonator, e.g., as described below.

In some demonstrative embodiments, the compensator may be configured to synchronize between frequencies of an adjustment of a multiplication factor of the frequency multiplier and the controlled oscillator, e.g., as described below. In some demonstrative embodiments, the frequency synchronization between the adjustment of the multiplication factor of the frequency multiplier and the controlled oscillator may be performed using a functionality of a Frequency Lock Loop (FLL), and/or any other mechanism, e.g., as described below.

In some demonstrative embodiments, the one or more attributes may include at least one attribute selected from the group consisting of a temperature of the solid state atomic resonator, a pressure on the solid state atomic resonator, an acceleration of the solid state atomic resonator, and a vibration of the solid state atomic resonator. In one example, the one or more attributes may include the temperature of the solid state atomic resonator, e.g., as described below.

As shown in FIG. **15**, in some demonstrative embodiments the atomic clock may also include one or more sensors, e.g., a temperature sensor, a pressure sensor, an acceleration sensor, a vibration sensor, and/or any other sensor to sense any other attribute.

As shown in FIG. **15**, in some demonstrative embodiments the atomic clock may also include a converter to convert a sensed attribute from the sensor. For example, as shown in FIG. **15** the atomic clock may include a filter, a temperature/pressure/acceleration and/or vibration to frequency multiplier converter, and a synchronized digital writer, e.g., as described below.

In some demonstrative embodiments, the solid state atomic clock may enable obtaining a frequency reference by generating a microwave signal with frequency, which corresponds to hyperfine splitting in the solid state material. The hyperfine splitting in the solid state material due to the RF signal may be detected by a photo diode. The photo diode's output signal and the temperature value, measured by the temperature sensor, may be used, for example, to adjust the microwave frequency, e.g., to that of the solid state material at a given temperature, e.g., as described below.

In some demonstrative embodiments, the output of the atomic clock may be the output of the voltage controlled crystal oscillator (VCXO). The VCXO may include a frequency oscillating generator which is able to change its output frequency according to a provided controlled signal as an input. In these embodiments, the VCXO may be controlled\tuned by the output voltage of the synchronous detector and loop filter, this line reflects the shifts that were detected from the atomic resonance frequency and is responsible for correcting these shifts. The VCXO's output may also, for example, be the reference source to the RF frequency synthesizer, which may provide an RF frequency signal to the physical package, e.g., as described below.

In some demonstrative embodiments, the RF frequency synthesizer may include an electronic device or circuit, which is capable of getting inputs of low frequencies and serial communications and generates multiplied, coupled, locked and modulated high frequency output signal, e.g., as described below.

In some demonstrative embodiments, the RF frequency synthesizer may include a frequency synthesizer, modulator and serial communication. The serial communication may be done between the RF frequency synthesizer and the Synchronizer. Through this connection the frequency multiplying factor that matches the current temperature may be updated on the RF synthesizer, e.g., as described below. The frequency multiplier may receive the current multiplying factor and may multiply the VCXO's low frequency signal to the desired high frequency RF signal. The value of the multiplier's output frequency may equal the product of the value of the input VCXO's frequency multiplied by a numerical factor. The multiplied frequency may be modulated by the Modulator, which may be configured to modulate the multiplied VCXO signal according to the low frequency oscillator's frequency. The RF frequency synthesizer's output may include a modulated high frequency microwave signal, which may match the current solid state resonance frequency, e.g., as described below.

In some demonstrative embodiments, the physical package may use an atomic resonance as the frequency reference. The physical package may receive as an input the output of the RF frequency synthesizer, and may generate an output error signal proportional to the difference between the internal resonance frequency of the resonator's atomic resonance and the RF frequency synthesizer output frequency. The physical package may include a light source, e.g., a LED, which may be configured to project light through the solid state resonator. The light may pass thorough the solid state material and interact continuously with the solid state resonator's NV centers. After passing the solid state resonator and interacting with the NV centers, the light may be sensed by a photo diode. The photo diode's output may be connected to the synchronous detector through loop filter, which generates a correcting signal to the VCXO.

In one example, a NV center in diamond may include a vacancy, e.g., absence of carbon atom, with a one Nitrogen substitute atom in one of the six atomic sites around the vacancy. It can be either Nitrogen or Nitrogen isotope as a substitute atom in the center. In its negative charge-state (NV−) this color center has very high photo stability and room temperature stability. It has a spin triplet (S=**1**) ground state **3**A and spin triplet (S=**1**) Exited state **3**E. The ground state has a very stable hyperfine zero field splitting of 2.88 GHz between the sublevels a spin singlet Sz (ms=**0**) and the spin doublet SxSy (ms=±1). The **3**A to **3**E ZPL transition is a spin conserving and has a very strong optical transition and high quantum efficiency. The ground state spin system can be pumped to the ms=**0** level by linear polarized optical excitation between the **3**A to **3**E energy states and then relaxation of those electrons to the ground ms=**0** sublevel. In addition, the photoemission transition of the color center from the exited state **3**E to the ms=**0** **3**A ground state energy levels is much stronger then the transition to the ms=**±1** **3**A ground state energy levels due to additional metastable energy level **1**A, which has strong non radiative energy transition to the ms=**0** **3** A ground state energy level. These two properties of the color center may allow, for example, to resolve optically the hyperfine structure of the ground state, e.g., by applying microwave excitation with a frequency equal substantially exactly to the hyperfine energy splitting frequency. This microwave radiation may excite the pumped electrons from the ms=**0** level to the ms=**1** level, thereby resulting in decreasing of the photoluminescence intensity.

The ZPL optical transition between the **3**A ground state and the **3**E exited state in the color center has very high quantum efficiency, which allows the luminescence detection of even a single optical center. The **3**A energy ground level is split due to the hyperfine energy splitting between the two ground energy levels. The lower level has spin splitting is 2.88 Ghz. The energy resonance can be read by optical—microwave resonance or by CPT. Diamond has a low phonon density, and therefore the interaction between the color center and the phonons in the diamond is low. The ground sate has long decoherence time of the electron spin state. Very sharp resonance line, relative to resonance lines of color centers in other materials, can be detected even at room temperature. The NV color center has wide absorption band from the ZPL at 637 nm and to less than 450 nm the emission band of the

NV center is from the ZPL at 637 nm to a vibronic emission band between 637 nm to 750 nm, which can be easily detected by a silicon photo detector. This absorption and emission resonance line and the adsorption and the emission lines band can be used to excite and measure the photo luminescence of the color center. Diamond is a highly stable material and a wide band-gap semiconductor material with a wide transparency window in the visible spectrum. It is a very good heat conductor and can be very good insulator or good conductor, e.g., upon doping.

In some demonstrative embodiments, the temperature to frequency converter may receive the measured temperature of the solid state material within the physical package from the temperature sensor after passing a filter.

In some demonstrative embodiments, the converter may generate an updated ("new") multiplying factor that matches the current solid state resonator status\temperature.

In one example, this compensation mechanism may be implemented by filtering the measured temperature, some filtering implementation may be used for this application such as sliding window averaging, moving average, discriminator, and the like. Using a filter reduces inaccuracies that may happen due to noise.

According to this example, a transform function of resonance frequency as temperature change may be calculated through measurements to adjust a specific resonance to a specific temperature. For example when using a first order transfer function with coefficient 74.3 [KHz/C deg], the following may apply: multiply factor=(0.00743*Degrees+0.041483). Different orders polynomial or other mathematical function may also be apply for higher precision.

According to this example, implementing the compensation mechanism may include generating a general compensation function by analytical or manual convergence of the transform function mentioned in the previous steps. After these steps, every temperature has its own frequency resonance stored. According to the current temperature level average, the RF synthesizer may be updated, for example, online by the temperature compensation mechanism to the suitable frequency of the resonance.

In some demonstrative embodiments, the multiplying factor update may be achieved through the synchronizer, which generates an update according to the low frequency oscillator's rising edge, thus reduces dramatically mismatches that may occur due to noise, etc. One demonstrative temperature update is illustrated in FIG. **16**. Other temperature updates may be implemented. In other embodiments, compensation for one or more additional or alternative attributes, e.g., pressure, acceleration, vibration, and the like, may be performed in a similar manner, e.g., in addition to or instead of the temperature compensation described above.

As shown in FIG. **16**, when Temperature changes, an immediate update to the temperature to frequency converter is done (top set of arrows). The converter may calculate the appropriate frequency to the current temperature, and may send an update to the frequency synchronizer (also referred to as "synchronizer") (lower set of arrows). The frequency synchronizer may update the multiply factor which the RF synthesizer holds after a change was detected to the Synchronizer data in. As shown in FIG. **16**, the update may be done synchronously to the rising edge of the low frequency oscillator, and in a specific time window (T) which reflects the exact needed writing time for a complete update, thus, for example, dramatically reducing mismatches that may occur due to noise, and the like.

FIG. **17** schematically illustrates a general block diagram of the frequency synchronizer, in accordance with some demonstrative embodiments. In some demonstrative embodiments, the frequency synchronizer may utilize a FLL mechanism and/or any other frequency synchronization mechanism.

As shown in FIG. **17**, the frequency synchronizer may receive as an input the low frequency oscillator signal, by using edge detect and triggering duty cycle to T %, data out may be, for example, updated, e.g., only at rising or falling edges or at any other timing. Clock up cycle may be determined to the exact needed time for temperature update. Using this mechanism may, for example, reduce noise and update temperature in an efficient manner.

In some demonstrative embodiments, for example if the RF synthesizer would be connected directly to the Temperature to Frequency converter, without the frequency synchronizer in the middle, unnecessary writing cycles may result in a waste of power and/or reduced immunity to noise. One exemplary disadvantage of these unnecessary writings is that the RF synthesizer's locking capabilities may be disrupted, which may bring the entire system to lose its precision. FIG. **18** schematically illustrates unwanted writing cycles, in accordance with some demonstrative embodiments.

In one example, the atomic clock can be implemented by a 10 Mhz VCXO, a 20 Hz square wave low frequency oscillator, a RF synthesizer FM modulator and two frequency multiplier registers, an Fup and Flow, a Green LED, a 540 nm green short pass optical filter, an NV centers enriched diamond, a 590 nm red long pass filter, an Si detector, a transimpedance amplifier, a synchronous detector, a loop filter, a temperature sensor, a temperature to voltage converter, an A/D converter, and voltage to frequency multiplier converter.

According to this example, the temperature sensor may be implemented by using 4 point probe temperature measurement, or any other implementation. A Thermistor or RTD may be used, for example, as the temperature probe in order to achieve high scale measurements. Each temperature may be reflected by different resistance of the Thermistor or RTD. This resistance may be, for example, sampled by an analog to digital converter (ADC) which provides, for example, at least 15 bit sampling ability, enabling span of −40-70 Celsius degrees with 0.001 degrees steps. The measured resistance may be transmitted to the temperature to frequency converter through serial communication.

In one demonstrative numerical example, at a temperature of 33.04° C. the resonance frequency of the diamond NV color centers is 2869.7 Mhz, and the frequency to temperature coefficient is 74.3 KHz/° C. The frequency multiplier may be set to equal to 286.97, e.g., in order to change the VCXO output frequency form 10 Mhz to 2869.7 Mhz. In case that the temperature is changed by 0.01° C., from 33.04° C. to 33.03° C., the resonance frequency may be, for example, changed from 2869.7 Mhz to 2869.700743 Mhz. Since the VCXO output frequency is locked to the atomic resonance, without temperature compensation the VCXO frequency will change to 10.00000259 MHz (2869.700743/286.97). If the frequency multiplier converter is working, then at the moment the temperature is changed, the frequency multiplier converter generates a new frequency multiplier which is equal to 286.9700743 and, as a result, the RF synthesizer output will be equal to 2869.700743, and the VCXO frequency output will remain 10 MHz. The FM frequency deviation may be 300 KHz, and therefore, the upper frequency multiplier, Fup, and lower frequency multiplier, Flow, may be equal to 286.985 and 286.955, respectively. Up on a temperature change of 0.01° C. from 33.04° C. to 33.03° C., the temperature to frequency multiplier converter may change the two frequency multipliers, Fup, and Flow to 286.9850743 and 286.9550743, respectively.

In some demonstrative embodiments, the FM modulator may be implemented, for example, by changing the multipliers Fup and Flow registers alternately at the low frequency oscillator rate, e.g., as shown in FIG. **19**. This may result in the modulation of the output frequency of the RF multiplier by the low frequency oscillator.

FIG. **1** schematically illustrates a SSAC in accordance with some demonstrative embodiments. In some non-limiting embodiments the SSAC **100** of FIG. **1** may perform the functionality of the SSAC of one or more of FIGS. **9-14**.

The method for obtaining a frequency reference is implemented by generating a microwave signal **413** by controlled oscillator **411** with a frequency corresponding to the resonance of quantum state **416**, the frequency of the microwave signal is compared **418** to that the resonance frequency **416** of hyperfine splitting of color center in solid state medium, the output signal **410** of the comparator **418** is used to adjust the microwave frequency to that of the color centers resonance frequency **416** and rescaling **414** of the microwave frequency to the required frequency and outputting the rescaled frequency **415**, whereby the output frequency refers to that of the color center resonance frequency. As shown in FIG. **8***b*

The SSAC may include a controlled oscillator **102**, a frequency multiplier **104**, a solid-state atomic resonator, and/or a feedback circuit **101**, e.g., as are described in detail below.

The controlled oscillator **102** is a frequency oscillating generator which is able to change its output frequency according to a provided controlled signal as an input. The frequency output of the controlled oscillator **102** may be multiplied, coupled and locked to the frequency resonance or energy resonance of the solid-state resonator. Therefore, a highly precise and stable frequency output may be obtained.

The frequency multiplier **104** is an electronic device or circuit which is capable of getting an input signal with a low frequency and generates an output signal with higher a frequency. The value of the output frequency equals to the value of the input frequency multiplied by a numerical factor sets to the frequency multiplier **104**. A The frequency multiplier **104** in FIG. **1** gets a relatively low frequency from the controlled oscillator **102** as an input and generates a signal with frequency corresponding to the resonator resonance frequency as an output. This frequency may be fed and/or coupled to the resonator module, e.g., via optical and/or microwave signals transmitter. The resonator module uses an atomic resonance to be used as a frequency reference. It may receive as an input the output of the frequency multiplier **104**, and generate an output error signal proportional to the difference between the internal resonance frequency of the resonator atomic resonance and the multiplier output frequency **107**.

The feedback circuit **101** may receive an output error signal **106** of the solid-state resonator module **103** as an input and generates an error correction signal **105** to the controlled oscillator **102**. The controlled oscillator **102** uses this error signal to correct its output frequency **108 109**, e.g., in order to reduce the error between the output frequency **107** of the frequency multiplier **104** and the solid-state resonator **219** resonance frequency. Accordingly, the output frequency **108** may be locked to the atomic resonance frequency of the solid-state atomic resonator **219**.

Feedback Circuit **101**:

The feedback circuit **101** may receive the resonator output error signal as an input and convert it into a correction signal to be provided to the controlled oscillator **102** module. The output signal of the atomic resonator module **106** may have an extremum in the output signal level, e.g., exactly at the frequency value where the input frequency and the internal resonance frequency of the atomic resonator **219** are equal. The atomic resonator module output error signal **106** is proportional to the difference between the frequency of the applied microwave signal **107** and the internal resonance frequency of the atomic resonator **219**. The error signal at the output of the atomic resonator **106** is provided to the input of the feedback circuit **101** may have a low signal to noise ratio. Therefore, a filtering and/or signal-processing scheme may be used in order to extract the error signal from the noise. For example, a synchronous detection scheme can be used in the feedback circuit **101** to detect very low signals in noise and to estimate the correct error signal. Since the SSAC may operate as a closed loop, a control system may be implemented, e.g., as part of the feedback circuit **101** and/or as part of any other element of the SSAC, to achieve maximum stability, minimum output frequency noise and/or Allan deviation. In one non limiting example, a PID control scheme can be implemented. In one non limiting example, a synchronous filter may be implemented for one non limiting example an Analog Device inc. AD630, AD633 balance modulator/demodulator. The PID scheme can be implemented with an operational amplifier (e.g., Analog Devices Inc. part number ADTL082) and passive electronic components.

Controlled Oscillator **102**:

The controlled oscillator **102** may include a frequency oscillator. The controlled oscillator **102** may receive an input signal from the feedback circuit **101** and convert it into a frequency output signal, which is corresponding to the signal level of the input signal. The controlled oscillator **102** may be implemented, for example, by a high Q factor voltage controlled oscillator **102**. In one non limiting example, a Voltage Controlled Crystal Oscillator (VCXO), which may include a low frequency oscillator based on a quartz crystal. The crystal oscillations may have very high Q factor and good short-term stability. However, it may have very poor long-term stability expressed in frequency drifting as the time elapse. These kinds of oscillators have an input controlled voltage, which allows change in the output frequency according to the input voltage level. The output frequency of the VCXO may be corrected according to the output signal generated by the feedback circuit **101**. In one non-limiting example, the VCXO may include a Vectron International V-800 VCXO, or equivalents, e.g., as described by A. Brannon, J. Breitbarth, and Z. Popovic, "A Low-Power, Low Phase Noise Local Oscillator for Chip-Scale Atomic Clocks," IEEE Microwave Theory and Techniques Symposium, in press, 2005, the entire disclosure of which is incorporated herein by reference.

Frequency Multiplier **104**:

The frequency multiplier **104** may receive a frequency input from the VCXO and multiply the frequency input to result in an output frequency equals to the value of the input frequency multiplied by a required factor. The output frequency may be substantially equal to the resonator frequency resonance, e.g., in the case of the electromagnetic microwave method described herein; or substantially half of this frequency, e.g., in the case of the CPT method described herein. In one non limiting example, the frequency multiplier **104** may use a PLL (Phase Lock Loop), FLL (Frequency Lock Look), frequency mixing and/or any other technique. These methods of frequency multiplication allow a frequency altering while keeping the phase noise low. In one non limiting example, the frequency multiplier **104** can be implementing, for example, by a DDS (Direct Digital Syntisizer), e.g., if advance frequency processing is required. The frequency multiplier **104** may be implemented, in one non-limiting example, using Analog Device inc. RF PLL Frequency Synthesizers such as AD809, ADF4212, ADF4213, ADF4218L, ADF4007 or equivalent.

Atomic Resonator Module **103**:

The atomic resonator module **103** may receive as an input a microwave frequency of an electro-magnetic signal as an input **107** from the frequency multiplier, which may be intended to be substantially equal to the internal frequency resonance of the resonator (In the case of CPT, a signal with half of this frequency is required as described herein). The atomic resonator may generate an output error signal **225** substantially equal to the difference between the input frequency **107** and an internal resonance frequency of the atomic resonator, e.g., as described below.

In some embodiments, the solid state atomic resonator module **103** may be implemented by as a double resonance resonator **199** which includes one or more of the following elements and/or modules, e.g., as described below:

An excitation light source **200**.

Light source power controller **201**.

Light source wavelength controller **202**.

An Optical processing elements include an optical polarization controller **204**, an optical attenuator **205** and/or and optical wavelength filter **206**.

A microwave amplifier **222**.

A microwave polarizer **221**.

A microwave transmitting antenna to transmit the microwave electromagnetic radiation upon the quantum resonant **220**.

An optical cavity **209**.

An atomic resonator element including a solid-state material **220** having an energy level system which may have hyperfine energy splitting, e.g., as described herein.

Light Polarizer **207**.

Optical filter **224**.

Photo-detector **226**.

Magnetic field shielding **207**.

In some embodiments, the solid state atomic resonator module **103** may be implemented by as a double resonance resonator **299** which includes one or more of the following elements and/or modules, e.g., as described below:

An excitation light source **300**.

Light source power controller **301**.

Light source wavelength controller **302**.

An Optical processing elements include an optical polarizer **306**, an optical attenuator **307** and/or and optical wavelength filter **308**.

A Microwave modulator, which can modulate the light source directly **303**;

An optical cavity **311**.

An atomic resonator **312** element including a solid-state material having an energy level system which may have hyperfine energy splitting, e.g., as described herein.

Light Polarizer **316**.

Optical filter **314**.

Photo-detector **315**.

Magnetic field shielding **310**.

FIG. **4** schematically illustrates a double resonance based solid-stat atomic resonator module **199** in accordance with one demonstrative embodiment. In some non-limiting embodiments the solid-state atomic resonator of FIG. **4** may perform the functionality of the SSAC of FIG. **1**

The solid-state atomic resonator module **199** of FIG. **4** may implement any suitable method for measurement of the resonance lines by a double resonance technique. In one non limiting example, the solid-state atomic resonator module **199** of FIG. **4** may implement a method for measurement of the resonance lines by a double resonance technique to get the atomic resonance. As describe by technique as described, for example, by T. P. Mayer Alegre, C. Santori, G. Medeiros-Ribeiro, and R. G. Beausoleil "Polarization-selective excitation of nitrogen vacancy centers in diamond" Physical Review B 76, 165205 (2007), the entire disclosure of which is hereby incorporated herein by reference.

A light source **200 302** with a wavelength controller **202 300** and power controller **201 301** may be implemented to illuminate a solid-state resonator **219 312**, e.g., as described herein, through a linear polarizer **204 306**, an optical attenuator **206 307** and an optical filter **206 308**. The wavelength of the illuminating light **203 305** can be but not limited to the Zero Phonon Line (ZPL) at 637 nm or at 532 nm, which can excite a Nitrogen Vacancy (NV) center in diamond from the ground level ^3A to the excited energy level ^3E, e.g., as described below. In non limiting example, pumping the NV centers in a diamond with a polarized light results in accumulation of the electrons in the ms=**0** state of the ^3A ground state. As a result the photo luminescence of the NV centers ground state energy splitting of NV center in diamond, may result in the transfer of electrons from the ms=**0** ground state of the ground state to the ms=**±1** state of the ground state, which may reach a minimum when the frequency is equal exactly to the ground state energy splitting.

FIG. **5** schematically illustrates a CPT based solid-state atomic resonator module **299** in accordance with another demonstrative embodiment. In some non-limiting embodiments the solid-state atomic resonator of FIG. **5** may perform the functionality of the SSAC of FIG. **1**.

The solid-state atomic resonator module **299** of FIG. **5** may implement any suitable method for measurement of the resonance lines by a CPT technique. In one non-limiting example, the solid-state atomic resonator module **103** of FIG. **5** may implement a method for measurement of the resonance lines by a CPT technique as described but limited to by Charles Santori et al. "Coherent Population Trapping of Single Spins in Diamond under Optical Excitation" Phys. Rev. Lett. 97, 247401 (2006), and/or Charles Santori et al. "Coherent Population trapping in diamond N-V centers at zero magnetic field" Vol. 14 No. 17 Opt. Exp. (2006), the entire disclosures of which are incorporated herein by reference.

A light source **302** with two coherent wavelengths may illuminate a solid-state resonator **312** through a linear polarizer **306**, an optical attenuator **307**, and an optical filter **308** e.g., as described herein. The wavelengths and power may be controlled such that the frequency difference between the two coherent wavelengths is tuned to be equal to the ground state splitting of 2.88 Ghz. This frequency difference in the light source wavelength is produced and controlled by an external microwave signal, which may be used as the frequency reference in the SSAC. The wavelengths of the illuminating light can be but not limited to the ZPL at 637 nm or at 532 nm or any other wavelength, which can excite the NV center from the ground energy level ^3A to one of the sublevels of the excited energy level ^3E e.g., as described below. In a non limiting example, illuminating the NV centers in the diamond may result in excitation of electrons from the ms=**0** and ms=**±1** ground level energy states to the excited state simultaneously. This simultaneous excitation will results in a CPT quantum state and, as a result, a dip in the photo luminescence or a peak in the transmission of the NV centers as function of the transmitted frequency value exists. This extremum occurs when the frequency of the microwave signal from the frequency multiplier **104** is exactly equal to the ground state energy splitting. Therefore, the controlling microwave frequency may be locked to the hyperfine transition.

The Solid State Resonator **219 312**

In some embodiments, the solid-state resonator may include a solid-state material including color centers in an optical cavity, e.g., as described herein. The color centers may be vacancies, e.g., a site where one atom is missing in the material matrix, or a vacancy with relation to one or more atom elements different from the solid-state material matrix. The solid-state material matrix can be single crystal, polycrystalline, nanocrystalline, amorphous or any other form. The color centers can be electrically neutral or charged. The atomic resonator may include a single color center or an ensemble of a large number of color centers. The color centers can be randomly scattered or ordered in the solid-state material matrix.

The solid-state material may be placed in an optical cavity as described below and/or as shown in FIG. **6**. The color centers may have hyperfine energy splitting in the ground energy state and may have one or more higher energy levels. Electrons from the ground states can be exited to one of these higher energy levels. The hyperfine resonance splitting can be read out by optical detected microwave radiation excitation or by optical detected CPT, e.g., as described herein. Electrons in the ground state can be exited by a coherent and/or non-coherent light source or by any other electro magnetic radiation. The photon energy or wavelength of the exiting radiation can be in the IR range, the visible range, or any other suitable photon energy.

The Optical Cavity **209 311**

In some non-limiting examples, The optical cavity **209 311** may include an optical cavity **209 311** as described, for example, by K. J. Vahala, "Optical microcavities", Nature (London) 424, 839 (2003); S. Haroche and D. Kleppner, "Cavity quantum electrodynamics", Physics Today, January 1989, pp. 24; Y. Yamamoto and R. Slusher, "Optical processes in microcavities," Physics Today, June 1993, pp. 66; C. J. Hood, T. W. Lynn, A. C. Doherty, A. S. parkins, and H. J. Kimble, "The atom-cavity; and/or microscope: single atoms bound in orbit by single photons," Science, vol. 287, No. 25, pp. 1447-1453 (2000), the entire disclosures of which are hereby incorporated herein by reference.

The optical cavity **209 311** may include a "narrow wavelength" multiple reflection cavity. Inside the cavity only photons with a wavelength matching the boundary conditions and the allowed optical mode are sustained. High intensity optical modes are generated inside the cavity. These modes interact continuously with the color center of the solid-state resonator **219 312**, to result in higher quantum efficiency and narrower absorption and emission lines. In one non limiting example, the optical cavity **209 311** may be implemented, for example, as part of the diamond material described above. In another non limiting example, the optical cavity **209 311** may be implemented separately, and the color centers may be incorporated to the cavity.

The NV centers may include micrometer diamond particles or nano diamond particles containing NV centers, or may be implemented as part of a solid slab of diamond. The optical cavity may be implemented using Fabry Perot, Bragg mirrors or Bragg Reflectors, photonic crystal resonator, external cavity, Fiber Bragg grating, membrane cavity, vertical cavity, micro-pillar vertical cavity, micro discs, Whispering gallery or any other optical cavity implementations, e.g., as shown in FIG. **6**.

The optical cavity **209 311** can be but not limited to one wavelength narrow band or dual band narrow wavelength, wherein one band can be tuned to the excitation wavelength and the other band can be tuned to the emission or luminescence wavelength. The optical cavity **209 311** may improve the emission/luminescence gain it improves the interaction of the incident light beam with the color centers. The optical cavity **209 311** may narrow the absorption band and the emission band, and may eliminate shifting and broadening of the zero phonon lined due to stress and/or other parameters.

Example of a NV Color Center in DIAMOND:

A specific description of NV color centers in diamond can be found, for example, in Torsten Gaebel et al. "Room-temperature coherent coupling of single spins in diamond" Nature Physics 2, 408-413 (2006); R. Hanson, 0. Gywat, and D. D. Awschalom "Room-temperature manipulation and decoherence of a single spin in diamond" Phys. Rev. B 74, 161203(R) (2006); R. Hanson, F. M. Mendoza, R. J. Epstein, and D. D. Awschalom "Polarization and Readout of Coupled Single Spins in Diamond" Phys. Rev. Lett. 97, 087601 (2006); N. B. Manson, J. P. Harrison, and M. J. Sellars "Nitrogen-vacancy center in diamond: Model of the electronic structure and associated dynamics" Phys. Rev. B 74, 103303 (2006); Ph. Tamarat et al. "The excited state structure of the nitrogen-vacancy center in diamond" arXiv:cond-mat/0610357v1 13 oct 2006; T. P. Mayer Alegre, A. C. Torrezan, G. Medeiros-Ribeiro "Microstrip resonator for microwaves with controllable polarization" Appl. Phys. Lett. 91, 204103 (2007); T. P. Mayer Alegre, C. Santori, G. Medeiros-Ribeiro, and R. G. Beausoleil "Polarization-selective excitation of nitrogen vacancy centers in diamond" Phys. Rev. B 76, 165205 (2007); A. P. Nizovtsev, S. Ya. Kilin, F. Jelezko, I. Popa, A. Gruber, J. Wrachtrup "NV centers in diamond: spin-selective photokinetics, optical ground-state spin alignment and hole burning" Physica B 340-342 (2003); and/or J. R. Rabeau et al. "Implantation of labeled single nitrogen vacancy centers in diamond using ^{15}N" Applied Physical Letters 88, 023113 (2006), the entire disclosure of which are incorporated herein by reference.

A NV center in diamond may include a vacancy, e.g., absence of carbon atom, with a one Nitrogen substitute atom in one of the six atomic sites around the vacancy as shown at FIG. **7***b*. It can be either Nitrogen or Nitrogen isotope as a substitute atom in the center. In its negative charge-state (NV−) this color center has very high photo stability and room temperature stability. It has a spin triplet (S=**1**) ground state ^{3}A and spin triplet (S=**1**) Exited state ^{3}E. The ground state has a very stable hyperfine zero field splitting of 2.88 Ghz between the sublevels a spin singlet Sz (ms=**0**) and the spin doublet Sx Sy (ms=±**1**). The ^{3}A to ^{3}E ZPL transition is a spin conserving and has a very strong optical transition and high quantum efficiency as shown at FIG. **7***a*. The ground state spin system can be pumped to the ms=**0** level by linear polarized optical excitation between the ^{3}A to ^{3}E energy states. and then relaxation of those electrons to the ground ms=**0** sublevel. In addition, the photoemission transition of the color center from the exited state ^{3}E to the ms=**0** ^{3}A ground state energy levels is much stronger then the transition to the ms=**±1** ^{3}A ground state energy levels due to additional metastable energy level ^{1}A, which has strong non radiative energy transition to the ms=o ^{3}A ground state energy level. These two properties of the color center may allow, for example, to resolve optically the hyperfine structure of the ground state, e.g., by applying microwave excitation with a frequency equal substantially exactly to the hyperfine energy splitting frequency. This microwave radiation may excite the pumped electrons from the ms=**0** level to the ms=**1** level, thereby resulting in decreasing of the photoluminescence intensity.

The ZPL optical transition between the ^{3}A ground state and the ^{3}E exited state in the color center has very high quantum efficiency, which allows the luminescence detection of even a single optical center. The ^{3}A energy ground level is split due to the hyperfine energy splitting between the two ground energy levels. The lower level has spin splitting is 2.88 Ghz. The energy resonance can be read by optical—microwave resonance or by CPT, e.g., as explained above. Diamond has a low phonon density, and therefore the interaction between the color center and the phonons in the diamond is low. The ground sate has long decoherence time of the electron spin state. Very sharp resonance line, relative to resonance lines of color centers in other materials, can be detected even at room temperature. The NV color center has wide absorption band from the ZPL at 637 nm and to less than 450 nm the emission band of the NV center is from the ZPL at 637 nm to a vibronic emission band between 637 nm to 750 nm, which can be easily detected by a silicon photo detector. This absorption and emission resonance line and the adsorption and the emission lines band can be used to excite and measure the photo luminescence of the color center. Diamond is a highly stable material and a wide band-gap semiconductor material with a wide transparency window in the visible spectrum. It is a very good heat conductor and can be very good insulator or good conductor, e.g., upon doping.

FIG. **7***a* schematically illustrates an energy level diagram of an NV color center.

FIG. **7***b* schematically illustrates a NV center structure in diamond lattice. The gray spheres represent the carbon atoms in the diamond lattice, the "N" sphere represent the nitrogen atom and the "V" sphere represents the vacancy an absence of an atom in the diamond lattice.

The NV color center formation and fabrication in DIAMOND is described, for example, in U.S. Pat. No. 4,880,613; and/or J. R. Rabeau et al. "Implantation of labeled single nitrogen vacancy centers in diamond using ^{15}N" Applied Physical Letters 88, 023113 (2006), the entire disclosure of which is incorporated herein by reference.

The NV color centers can be found with various concentrations in natural diamond both in type IIa and in type Ib. In order to create NV color centers in diamond, with a controlled concentration and dispersion, usually a type IIa or type Ib natural or synthetic diamond with a very low level up to a very high level of nitrogen content is irradiated by neutron, electrons or ions which creates vacancies in the diamond lattice. These vacancies defuse to nitrogen sites upon annealing in temperature of 600 to 1100 centigrade to create NV color centers, e.g., as shown in FIG. **7***b*.

In some non-limited examples, the SSAC described herein can be integrated, for example, as a discrete component, e.g., including all of the components of the SSAC.

As shown in FIG. **8***a*, in one non-limiting example, the atomic clock described herein may be implemented as a chip-scale atomic clock **402**. For example, the atomic clock may be integrated as part of a semiconductor chip **400**. The semiconductor chip may include the whole set of electronic circuits as integrated circuits **401**, e.g., including the photo detector **405** and/or the light source **403** of the atomic clock. The atomic resonator **404** of the atomic clock may be implemented as part of the substrate **400**, or inserted on top of the substrate.

The color-center SSAC described herein may have at least one or more of the following advantages, e.g., compared to gas based atomic clocks, e.g., Rb/Cs gas based atomic clocks:

1. No toxic, volatile or other non-hazardous materials are used in the solid-state resonator.
2. The SSAC may not require constant heating of the resonator, and therefore may have lower power consumption, e.g., compared to the gas cell based atomic clock which has to be heated at all times in order to reach a proper operation this result in higher power consumption.
3. The Resonance medium in SSAC may include a solid-state material with size of less then a millimeter square. The manufacturing cost is of such resonator is very low, e.g., compared to the gas cell which has very complicated manufacturing process.
4. The optical excitation wavelength has a wide range, e.g., from 630 nm to less than 450 nm. This may allow the implementation of the light source by low cost solid state VIS light source.
5. The florescence wavelength has a wide range, e.g., from 630 nm to more than 700 nm, which may allow using a low cost Silicone photodetector.
6. Low size—The SSAC resonator may include a solid crystal embedded by color centers, wherein the size of the color center may be few nanometers, such that, for example, in one millimeter square up to 10 can be found. Therefore, the size of the resonator can be less than one micron thick.
7. G-force durability—inherently gases are much more sensitive to G-forces than solids. Applying G-force to gas result in a compression of the gas creating in homogeneous gas density. Therefore, light passing the gas experiencing different atom densities, this leads to intensity instability during this episode. This instability results in instability in the output frequency signal.
8. Aging—The aging in the SSAC, e.g., in diamond based solid-state atomic clock, may be significantly smaller compared to the gas base atomic clock. The atom gas cell is subject to aging due to release of residual gas molecule from the cell walls, adhesives and diffusion. Therefore the purity of the gas mixture is degraded during operation and as a result the performance of the atomic clock is degraded. On the other hand the SSAC may be based on diamond, e.g., as described above, which is one of the most stable materials.
9. No wear-out phenomena associated with Rubidium standards.
10. Very short warm up time, e.g., compared to long worm up time of gas base atomic clock.
11. Low power consumption—in gas resonators the gas cell has to be heated continually in order to achieve proper operation, which results in high power consumption. This may not be required in the SSAC resonator described herein.

Additionally or alternatively, the color-center SSAC described herein may have at least one or more of the following advantages: the material in which the color centers are embedded has a wide optical transparency. Therefore the color center can be addressed by optical means. The quantum state of the color center can be optically prepared and/or readout of the color-center SSAC described herein may have a reduced degree of sensitivity to electrical noise.

Additionally or alternatively, the color-center SSAC described herein may have at least one or more of the following advantages, e.g., compared to OCXO (Oven Controlled Crystal Oscillator) clocks, e.g., the Vectron TC-140 Temperature Compensated Quartz Crystal Oscillator:

1. Higher temperature stability than that of the OCXO.
2. Improve Long term frequency stability (Over long periods of time—days, week or months—their frequency will drift around).
3. Lower power consumption.
4. Smaller size.

5. Lower cost—he OCXO has low manufacturing yield of the resonator.
6. G-shock under applied external acceleration the quarts crystal is subject to a Newtonian force. This force will change and deform the quartz crystal as a result in an error in the output frequency, which is directly derived from the physical dimension of the crystal, will occur.
7. Aging—long term deformation, change in the internal strain and mass diffusion results in the change of the resonance frequency of the OCXO resonator.
8. Short worm up time.

Some embodiments may include an atomic clock frequency generator ("the Solid State Atomic Clock (SSAC)") to generate an accurate and/or stable output frequency based, for example, on an atomic resonance in the solid state material, e.g., as described below. The SSAC may be implemented as part of any suitable device, module, element, and/or system, e.g., as described below.

A generic electronic module and/or system utilizing a frequency standard SSAC is schematically illustrated in FIG. **8***c*. the module and/or the system comprising a input circuit which receives the input data, an output circuit which transmitter the output dada, a central processing unit (CPU), a memory unit, RF circuit, analog and/or digital circuits and a solid state atomic clock. This electronic module and/system can serves as a whole or in part to implement each of the applications describes below.

FIG. **9***a* schematically illustrates a Global Positioning System (GPS) in accordance with some demonstrative embodiments. Global positioning systems may require very high clock accuracy in order to acquire a system position. This accurate frequency can be stored by, provided by high accuracy local oscillator or frequency standard or SSAC, or retrieved from one of the GPS satellites; however it is not immune to jamming and other interferences a high accuracy local oscillator or frequency standard is requires in order to hold the reference frequency and to improve synchronization of the receiver. In portable anti-jam GPS applications small size, low power consumption and low cost frequency reference is required. Such high accuracy, small size, low power consumption and low cost local frequency reference oscillator or frequency standard can be realized by a SSAC e.g., as is described herein.

FIG. **9***b* schematically illustrates a cellular base station in accordance with some demonstrative embodiments. Cellular base station may use a frequency standard for example but limited to, holdover of cellular handset between base stations. Moreover, modern Base Station Backhaul may be based on Internet protocol (IP) backhaul, maintaining high service level assurance precise frequency distribution throughout the network is required. The transmission of voice, video and data in mobile networks requires a stable and precise frequency reference, and precise frequency synchronization is critical for the successful call signal hand-off between base stations. One possible solution for maintaining such stable and precise frequency reference is by employing a SSAC, e.g., as described herein.

FIG. **9***c* schematically illustrates a secure communication system in accordance with some demonstrative embodiments. It can use, but mot limited to for example a "time sequence code acquisition" for secure communication or any other method for secure communication based on precise timing. A secure communications system may use very accurate frequency for encryption of the information and the communication. One possible solution for maintaining such stable and precise frequency reference is by employing a SSAC, e.g., as described herein.

FIG. **10***a* schematically illustrates a cellular positioning system in accordance with some demonstrative embodiments. A Cellular positioning system may use high accuracy frequency to determine the distance between the cellular receiver and the cellular base station by measuring the Time of Arrival (TOA) of an electromagnetic pulse between the base station an the cellular receiver. One possible solution for maintaining such stable and precise frequency reference is by employing a SSAC, e.g., as described herein.

FIG. **10***b* schematically illustrates an Internet Protocol TV (IPTV) system in accordance with some demonstrative embodiments. An IPTV broadcast is based on Internet protocol (IP) backhaul, maintaining high service level assurance therefore, a precise frequency distribution throughout the network is required. The transmission of video and data in IP networks requires a stable and precise frequency reference, and precise frequency synchronization is critical for the successful timing reconstruction of the video signals in servers and network switches as well as at the end user system. One possible solution for maintaining such stable and precise frequency reference is by employing a SSAC, e.g., as described herein.

FIG. **10***c* schematically illustrates spread spectrum hopping radio communication system in accordance with some demonstrative embodiments. Very fast frequency hopping radio communication may include any suitable radio communication system, which sends the data over a wideband of frequencies by hopping between different frequencies. In very fast frequency hopping radio communication the radio receiver and transmitter should be frequency synchronized for long periods of time with out actively synchronization between the two radio systems. Such a radio system can be a military radio, civilian radio, wireless radio communication, cellular communication, WiMax, WiFi, spread spectrum communication or any other hopping radio communication. One possible solution for maintaining such stable and precise frequency reference is by employing a SSAC, e.g., as described herein.

FIG. **11***a* schematically illustrates a communication station in accordance with some demonstrative embodiments. Communication networks require maintaining a precise frequency distribution throughout the network. The transmission of voice, video and data in mobile networks requires a stable and precise frequency reference, and precise frequency synchronization and holding is critical for the successful communication between stations. One possible solution for maintaining such stable and precise frequency reference is by employing a SSAC, e.g., as described herein.

FIG. **11***b* schematically illustrates a cellular handset receiver with a positioning and/or range measuring system in accordance with some demonstrative embodiments. A range finding system, velocity measurement system on a cellular handset may use high accuracy frequency to determine the distance between the transmitter/receiver and the object by Time of Arrival (TOA) algorithm or any other algorithm, and/or highly accurate clock may be use for hold over proposes. One possible solution for maintaining such stable and precise frequency reference is by employing a SSAC, e.g., as described herein.

FIG. **11***c* schematically illustrates cellular handset receiver with a holdover system in accordance with some demonstrative embodiments. Holdover system between two base stations of cellular system on a cellular handset may use high accuracy frequency to determine the distance between the transmitter/receiver and the object by Time of Arrival (TOA) algorithm or any other algorithm, and/or highly accurate clock may be use for hold over proposes. A possible solution for maintaining such stable and precise frequency reference is by employing a SSAC, e.g., as described herein.

FIG. **12***a* schematically illustrates a burst radio communication system in accordance with some demonstrative embodiments. Burst radio communication may include any suitable radio communication system, which sends bursts of voice, video or data over a radio frequency. In this type of systems the radio receiver and transmitter should have precise frequency synchronization for long periods of time with out actively synchronization between the two radio systems. Such a radio system can be a military radio, civilian radio, wireless radio communication, cellular communication or any other hopping radio communication. One possible solution for maintaining such stable and precise frequency reference is by employing a SSAC, e.g., as described herein.

FIG. **12***b* schematically illustrates an Identification Friend or Foe (IFF) module in accordance with some demonstrative embodiments. An IFF system using radio communication, e.g., to identify a flying aircraft, may use high accuracy frequency for the radio communication. One possible solution for maintaining such stable and precise frequency reference is by employing a SSAC, e.g., as described herein.

FIG. **12***c* schematically illustrates a measuring system in accordance with some demonstrative embodiments. In a measuring system for example jitter/wonder measuring, radio frequency measurement systems, or other measuring systems, need a high accuracy frequency time base. One possible solution for maintaining such stable and precise frequency reference is by employing a SSAC, e.g., as described herein.

FIG. **13***a* schematically illustrates a time-server in accordance with some demonstrative embodiments. A time-server may include any suitable a communication network component with precise time keeping ability. The time-server may be connected to the communication network and it can send time indicator to other components of the network. The time-server can be a stand-alone or embedded in to another system in the network such servers, switches or hubs. One possible solution for maintaining such stable and precise frequency reference is by employing a SSAC, e.g., as described herein.

FIG. **13***b* schematically illustrates a precise network analyzer system in accordance with some demonstrative embodiments. The precise network measuring system may include any suitable communication network component, which monitors the performance of the communication network in order to measure Quality of the service including intrusion detection, lost of packets and other requirements. The system may require precise time keeping ability to log precisely any occurring event in the network. The system is connected to the communication network and can be a stand alone or embedded in to other systems in the network such servers, switches or hubs. One possible solution for maintaining such stable and precise frequency reference is by employing a SSAC, e.g., as described herein.

FIG. **13***c* schematically illustrates a billing system in accordance with some demonstrative embodiments. A network communication billing system may include any suitable communication network component, which monitors the traffic of the communication network in order to bill for the service and usage. The system may require precise time keeping ability to log precisely any usage of the network. The system is connected to the communication network and can be a stand alone or embedded in to other systems in the network such servers, switches or hubs. One possible solution for maintaining such stable and precise frequency reference is by employing a SSAC, e.g., as described herein.

FIG. **14***a* schematically illustrates a radar system in accordance with some demonstrative embodiments. The radar system may measure the direction, distance and/or velocity of an object by Time of Arrival (TOA) of an echo radio wave signal. High accuracy frequency source is used to determine the TOA. One possible solution for maintaining such stable and precise frequency reference is by employing a SSAC, e.g., as described herein.

FIG. **14***b* schematically illustrates a time-server in accordance with some demonstrative embodiments. A time stamp server may include any suitable communication network component with precise time keeping ability. The time stamp server is connected to the communication network and it can send time stamp to other users or components of the network and/or for other local applications in the system, for accurate time marking. The time stamp server can be a stand-alone module or embedded into another system in the network such servers, switches or hubs. This time stamp can be used for finance transaction time marking, B**2**B time marking, invoice time marking, billing time marking or any other application which requires time marking. One possible solution for maintaining such stable and precise frequency reference is by employing a SSAC, e.g., as described herein.

FIG. **14***c* schematically illustrates a sonar system in accordance with some demonstrative embodiments. The sonar system may measure the direction, distance and/or velocity of an object by Time of Arrival (TOA) of an echo of a sound wave signal. High accuracy frequency source is used to determine the TOA. One possible solution for maintaining such stable and precise frequency reference is by employing a SSAC, e.g., as described herein.

Some embodiments may be related to one or more of the following references, the entire disclosures of which are incorporated herein by reference:

P. Misra and M. Pratt, Role of the Clock in a GPS Navigation Receiver, ATC Project Memorandum No. 42PM-SATNAV-0008, Massachusetts Institute of Technology, Lincoln Laboratory (May 1994).

M. A. Sturza, GPS Navigation using Three Satellites and a Precise Clock, Global Positioning Systems, vol. II, Washington, D.C.: The Institute of Navigation, pp. 122-131 (1984).

J. H. Murphy and T. A. Skidmore; A Low-Cost Atomic Clock: Impact on the National Airspace and GNSS Availability; Proceedings of IONGPS-94; Salt Lake Convention Center, Salt Lake City, Utah Sep. 20-23, 1994; pp. 1-8.

J. Vig, "Military applications of high-accuracy frequency standards and clocks," 40, 522-527 (1993).

H. Fruehoff, "Fast "direct-P(Y)" GPS signal acquisition using a special portable clock," in Pro. c 33rd Ann.

Precise Time and Time Interval (PTTI) Systems and Applications Meeting, Long Beach, Calif., November 27-29, 359-369 (2001).

J. A. Kusters and C. A. Adams, "Performance requirements of communication base station time standards," RF design, 28-38 (1999).

L. Liew, S. Knappe, J. Moreland, H. G. Robinson, L. Hollberg, and J. Kitching, "Microfabricated alkali atom vapor cells," Appl. Phys. Lett. 48, 2694-2696 (2004).

S. Knappe, V. Velichansky, H. G. Robinson, L. Liew, J. Moreland, J. Kitching, and L. Hollberg, "Atomic Vapor Cells for Miniature Frequency References," in Proc. of the 2003 IEEE International Frequency Control Symposium and PDA Exhibition Jointly with the 17th European Frequency and Time Forum, (Institute of Electrical and Electronics Engineers, New York, 2003), 31-32.

E. Arimondo, "Coherent population trapping in laser spectroscopy," in, *Progress in Optics XXXV*, E. Wolf, eds. (Elsevier, Amsterdam, 1996), pp. 257-354.

M. Stähler, R. Wynands, S. Knappe, J. Kitching, L. Hollberg, A. Taichenachev, V. Yudin, "Coherent population trapping resonances in thermal Rb-85 vapor: D-1 versus D-2 line excitation," Opt. Lett 27, 1472-1474 (2002).

N. Cyr, M. Tetu, and M. Breton, "All-Optical Microwave Frequency Standard—a Proposal," *IEEE Transactions on Instrumentation and Measurement*, vol. 42, pp. 640-649, 1993.

J. Kitching, S. Knappe, N. Vukicevic, L. Hollberg, R. Wynands, and W. Weidmann, "A microwave frequency reference based on VCSEL-driven dark line resonances in Cs vapor," *IEEE Transactions on Instrumentation and easurement*, vol. 49, pp. 1313-1317, 2000.

M. Merimaa, T. Lindvall, I. Tittonen, and E. Ikonen, "All-optical atomic clock based on coherent population trapping in Rb-85," *Journal of the Optical Society of America B-Optical Physics*, vol. 20, pp. 273-279, 2003.

J. Kitching, S. Knappe, and L. Hollberg, "Miniature vapor-cell atomic-frequency references," *Applied Physics Letters*, vol. 81, pp. 553-555, 2002.

Some embodiments of the invention, for example, may take the form of an entirely hardware embodiment, an entirely software embodiment, or an embodiment including both hardware and software elements. Some embodiments may be implemented in software, which includes but is not limited to firmware, resident software, microcode, or the like.

Furthermore, some embodiments of the invention may take the form of a computer program product accessible from a computer-usable or computer-readable medium providing program code for use by or in connection with a computer or any instruction execution system. For example, a computer-usable or computer-readable medium may be or may include any apparatus that can contain, store, communicate, propagate, or transport the program for use by or in connection with the instruction execution system, apparatus, or device.

In some embodiments, the medium may be an electronic, magnetic, optical, electromagnetic, infrared, or semiconductor system (or apparatus or device) or a propagation medium. Some demonstrative examples of a computer-readable medium may include a semiconductor or solid-state memory, magnetic tape, a removable computer diskette, a random access memory (RAM), a read-only memory (ROM), a rigid magnetic disk, and an optical disk. Some demonstrative examples of optical disks include compact disk-read only memory (CD-ROM), compact disk-read/write (CD-R/W), and DVD.

In some embodiments, a data processing system suitable for storing and/or executing program code may include at least one processor coupled directly or indirectly to memory elements, for example, through a system bus. The memory elements may include, for example, local memory employed during actual execution of the program code, bulk storage, and cache memories which may provide temporary storage of at least some program code in order to reduce the number of times code must be retrieved from bulk storage during execution.

In some embodiments, input/output or I/O devices (including but not limited to keyboards, displays, pointing devices, etc.) may be coupled to the system either directly or through intervening I/O controllers. In some embodiments, network adapters may be coupled to the system to enable the data processing system to become coupled to other data processing systems or remote printers or storage devices, for example, through intervening private or public networks. In some embodiments, modems, cable modems and Ethernet cards are demonstrative examples of types of network adapters. Other suitable components may be used.

Reference is made to FIG. **20**, which schematically illustrates a product of manufacture **2000**, in accordance with some demonstrative embodiments. Product **2000** may include a non-transitory machine-readable storage medium **2002** to store logic **2004**, which may be used, for example, to perform at least part of the functionality of SSAC **100** (FIG. **1**), radio **106** (FIG. **1**), and/or SSAC **1500** (FIG. **15**) and/or to perform one or more operations of a method of generating a frequency reference, e.g., as described herein. The phrase "non-transitory machine-readable medium" is directed to include all computer-readable media, with the sole exception being a transitory propagating signal.

In some demonstrative embodiments, product **2000** and/or machine-readable storage medium **2002** may include one or more types of computer-readable storage media capable of storing data, including volatile memory, non-volatile memory, removable or non-removable memory, erasable or non-erasable memory, writeable or re-writeable memory, and the like. For example, machine-readable storage medium **2002** may include, RAM, DRAM, Double-Data-Rate DRAM (DDR-DRAM), SDRAM, static RAM (SRAM), ROM, programmable ROM (PROM), erasable programmable ROM (EPROM), electrically erasable programmable ROM (EE-PROM), Compact Disk ROM (CD-ROM), Compact Disk Recordable (CD-R), Compact Disk Rewriteable (CD-RW), flash memory (e.g., NOR or NAND flash memory), content addressable memory (CAM), polymer memory, phase-change memory, ferroelectric memory, silicon-oxide-nitride-oxide-silicon (SONOS) memory, a disk, a floppy disk, a hard drive, an optical disk, a magnetic disk, a card, a magnetic card, an optical card, a tape, a cassette, and the like. The computer-readable storage media may include any suitable media involved with downloading or transferring a computer program from a remote computer to a requesting computer carried by data signals embodied in a carrier wave or other propagation medium through a communication link, e.g., a modem, radio or network connection.

In some demonstrative embodiments, logic **2004** may include instructions, data, and/or code, which, if executed by a machine, may cause the machine to perform a method, process and/or operations as described herein. The machine may include, for example, any suitable processing platform, computing platform, computing device, processing device, computing system, processing system, computer, processor, or the like, and may be implemented using any suitable combination of hardware, software, firmware, and the like.

In some demonstrative embodiments, logic **2004** may include, or may be implemented as, software, a software module, an application, a program, a subroutine, instructions, an instruction set, computing code, words, values, symbols, and the like. The instructions may include any suitable type of code, such as source code, compiled code, interpreted code, executable code, static code, dynamic code, and the like. The instructions may be implemented according to a predefined computer language, manner or syntax, for instructing a processor to perform a certain function. The instructions may be implemented using any suitable high-level, low-level, object-oriented, visual, compiled and/or interpreted programming language, such as C, C++, Java, BASIC, Matlab, Pascal, Visual BASIC, assembly language, machine code, and the like.

Functions, operations, components and/or features described herein with reference to one or more embodiments, may be combined with, or may be utilized in combination with, one or more other functions, operations, components and/or features described herein with reference to one or more other embodiments, or vice versa.

While certain features of the invention have been illustrated and described herein, many modifications, substitutions, changes, and equivalents may occur to those skilled in the art. It is, therefore, to be understood that the appended claims are intended to cover all such modifications and changes as fall within the true spirit of the invention.

What is claimed is:

1. An apparatus comprising:

a solid-state atomic clock to generate a clock frequency signal, the solid-state atomic clock comprising:

a solid state atomic resonator comprising a solid-state material comprising an optical cavity haying color centers, which are capable of exhibiting hyperfine transition, wherein the solid-state atomic clock is configured to generate the clock frequency signal based on a hyperfine resonance frequency of said color centers; and

a compensator configured to compensate for a change in one or more attributes of said solid state atomic resonator, which are to affect said hyperfine resonance frequency of said color centers.

2. The apparatus of claim **1**, wherein said compensator comprises:

at least one sensor to sense said one or more attributes of said solid state atomic resonator; and

a frequency adjuster configured to cause an adjustment of said clock frequency signal based on the one or more sensed attributes of said solid state atomic resonator.

3. The apparatus of claim **1**, wherein the solid-state atomic clock comprises a solid-state atomic resonator module comprising the solid state atomic resonator,

wherein the solid-state atomic resonator module is configured to receive an input frequency signal, which is based on said clock frequency signal,

and wherein said compensator is to compensate for the change in said One or more attributes of said solid state atomic resonator by adjusting said input frequency signal to said solid-state atomic resonator module based on the one or more attributes of said solid state atomic resonator.

4. The apparatus of claim **1**, wherein the solid-state atomic clock comprises a solid-state atomic resonator module comprising the solid state atomic resonator,

wherein the solid-state atomic resonator module is configured to receive an input frequency signal, which is based on said clock frequency signal,

and wherein the solid-state atomic resonator module is configured to generate an error frequency signal proportional to a difference between the input frequency signal and the hyperfine resonance frequency of said color centers.

5. The apparatus of claim **4**, wherein the solid-state atomic clock comprises:

a feedback circuit configured to generate an error-correction signal based on the error frequency signal provided. by said solid-state atomic resonator module;

a controlled oscillator configured to generate said clock frequency signal based on said error-correction signal; and

a frequency multiplier configured to generate said input, frequency signal to said solid-slate atomic resonator module by multiplying a frequency of said clock frequency signal.

6. The apparatus of claim **5**, wherein said compensator is configured to compensate for the change in said one or more attributes of said solid state atomic resonator by causing said frequency multiplier to adjust said input frequency signal to said solid-state atomic resonator module based on the one or more attributes of said solid state atomic resonator.

7. The apparatus of claim **6**. wherein said compensator is configured to synchronize frequencies between an adjustment of a multiplication factor of said frequency multiplier and said controlled oscillator.

8. The apparatus of claim **4**, wherein the solid-state atomic resonator module comprises a light source configured to generate light to illuminate said solid-state atomic resonator, and a photo detector configured to generate the error frequency signal based on detected photo-luminescence of said color centers.

9. The apparatus of claim **1**, wherein said one or more attributes comprise at least one attribute selected from the group consisting of a temperature of said solid state atomic resonator, a pressure on said solid state atomic resonator, an acceleration of said solid state atomic resonator, and a vibration of said solid state atomic resonator.

10. The apparatus of claim **1**, wherein said solid-state material comprises diamond, and wherein the color centers comprise Nitrogen-Vacancy color centers in said diamond.

11. The apparatus of claim **1**, wherein said solid-state material comprises:

at least one diamond crystal embedded by Nitrogen-Vacancy color centers.

12. The. apparatus of claim **11**, wherein said at least one diamond crystal comprises

a plurality of nano-crystals.

13. The apparatus of claim **1**, wherein the optical cavity is formed by a plurality of bragg reflectors.

14. The apparatus of claim **1**, wherein the optical cavity is formed by a photonic crystal structure.

15. The apparatus of claim **1** comprising an integrated circuit comprising said solid-state atomic clock.

16. A method of obtaining a frequency reference, the method comprising:

causing color centers of a solid state atomic resonator to exhibit hyperfine transition, said solid state atomic resonator comprising a solid-state material comprising an optical cavity having said color centers;

compensating for a change in one or more attributes of said solid state atomic resonator, which are to affect said hyperfine resonance frequency of said color centers; and

generating a clock frequency signal based on the hyperfine resonance frequency of said color centers.

17. The method of claim **16**, wherein said compensating comprises:

sensing said one or more sensed attributes of said solid state atomic resonator: and

adjusting said clock frequency signal based on the one or more sensed attributes of said solid state atomic resonator.

18. The method of claim **16** comprising:

determining an error frequency based on the clock frequency signal and the hyperfine resonance frequency of said color centers; and

adjusting said clock frequency signal based on said error frequency.

19. A system comprising:

at least one electronic device comprising:

a solid-state atomic clock to generate a dock frequency signal, the solid-state atomic clock comprising:

a solid state atomic resonator comprising a solid-state material comprising an optical cavity having color centers, which are capable of exhibiting hyperfine transition, wherein the solid-state atomic clock is configured to generate the clock frequency signal based on a hyperfine resonance frequency of said color centers; and

a compensator configured to compensate for a change in one or more attributes of said solid state atomic resonator, which are to affect said hyperfine resonance frequency of said color centers; and

at least one electronic module to receive said clock frequency signal and perform an operation based on the clock frequency signal.

20. The system of claim **19**, wherein said compensator comprises:

at least one sensor to sense said one or more attributes of said solid state atomic resonator; and

a frequency adjuster to cause an adjustment of said clock frequency signal based on the one or more sensed attributes of said solid state fatomic resonator.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 9,360,844 B2
APPLICATION NO. : 14/760147
DATED : June 7, 2016
INVENTOR(S) : Gan

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In the claims

Column 29, line 57, claim 5, delete "provided." and insert -- provided --, therefor.

Column 29, line 62, claim 5, delete "input," and insert -- input --, therefor.

Column 29, line 63, claim 5, delete "solid-slate" and insert -- solid-state --, therefor.

Column 30, line 51, claim 17, delete "resonator:" and insert -- resonator; --, therefor.

Column 30, line 63, claim 19, delete "dock" and insert -- clock --, therefor.

Signed and Sealed this
Fourth Day of October, 2016

Michelle K. Lee

Michelle K. Lee
Director of the United States Patent and Trademark Office